ARL 63-58

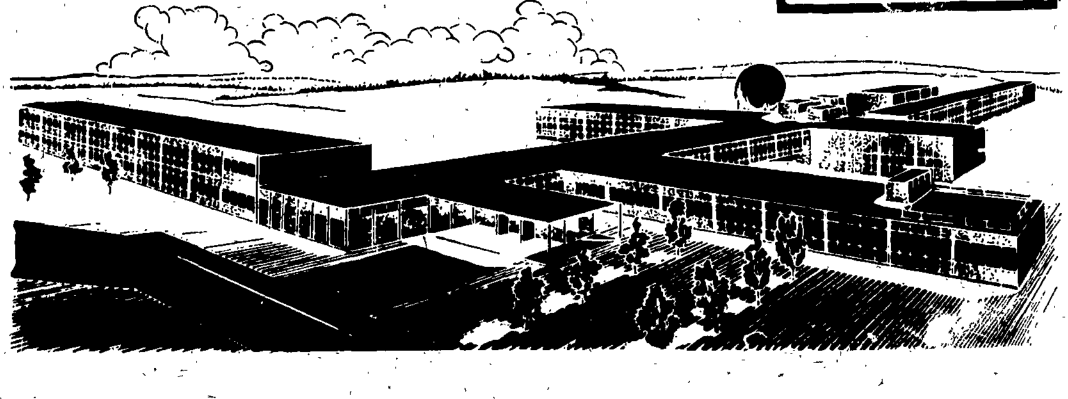
EXPERIMENTAL EVALUATION OF A DUAL-ELEMENT TRANSDUCER FOR HIGH-TEMPERATURE-GAS MEASUREMENTS

J. T. CHAMBERS
D. L. RALL
W. H. GIEDT

ADVANCED TECHNOLOGY LABORATORIES
A DIVISION OF AMERICAN-STANDARD
MOUNTAIN VIEW, CALIFORNIA

MARCH 1963

AERONAUTICAL RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE



NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

- - - - - - - - - -

Qualified requesters may obtain copies of this report from the Armed Services Technical Information Agency, (ASTIA), Arlington Hall Station, Arlington 12, Virginia.

- - - - - - - - - -

This report has been released to the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C. for sale to the general public.

- - - - - - - - - -

Copies of ARL Technical Documentary Reports should not be returned to Aeronautical Research Laboratory unless return is required by security considerations, contractual obligations, or notices on a specific document.

AF-WP-L-APR 62 100

30-738, 400, 6-11-63

ARL 63-58

EXPERIMENTAL EVALUATION OF A DUAL-ELEMENT TRANSDUCER FOR HIGH-TEMPERATURE-GAS MEASUREMENTS

J. T. CHAMBERS
D. L. RALL
W. H. GIEDT

ADVANCED TECHNOLOGY LABORATORIES
A DIVISION OF AMERICAN-STANDARD
MOUNTAIN VIEW, CALIFORNIA

MARCH 1963

CONTRACT AF 33(657)-8411
PROJECT 7063
TASK 7063-01

AERONAUTICAL RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This final technical report was prepared by the Advanced Technology Laboratories, A Division of American Radiator and Standard Sanitary Corporation, Mountain View, California, on Contract AF 33(657)-8411 for the Aeronautical Research Laboratories, Office of Aerospace Research, United States Air Force. The work reported herein was accomplished on Task 7063-01, "Research in Heat Transfer Phenomena," of Project 7063, "Mechanics of Flight," under the technical cognizance of Capt. T. Andrada of the Thermo Mechanics Research Laboratory of ARL.

ABSTRACT

An experimental evaluation was made of a dual-element transducer, in which gas-stream temperatures are inferred from simultaneous temperature-time measurements of two transducers of equal shape but unequal thermal capacity. The major effort was expended on measuring medium-temperature streams to prove the feasibility of the concept. The accuracy of the transducer was within ±6% in measurements from 1950 to 2250°F, which was the best experimental accuracy predicted by an earlier analysis of the concept. A limited number of measurements were made with the transducer directly in an oxyacetylene flame. The indicated flame temperatures were 4700°F and 4789°F, which agree within 5% with measurements made by sodium-line-reversal techniques for equivalent combustion conditions in tests conducted at the University of California. In a third series of tests, the transducer was used to traverse a 2100°F gas stream, and from a single record the temperature profile in the stream was calculated within the accuracy to which the true profile could be established. It is concluded that the dual-element transducer is feasible for all the applications tested. Recommendations are made for continued improvement.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF SYMBOLS

SYMBOL		DEFINITION
A	-	surface area of thermocouple (ft^2)
B	-	constant in convection equation (dimensionless)
C	-	constant of integration
c	-	heat capacity of thermocouple (Btu/lb-°F)
d	-	diameter of thermocouple (ft; in.)
F	-	combined geometric and emissivity factor (dimensionless)
F'	-	geometric factor (dimensionless)
h	-	convection coefficient (Btu/hr-ft^2-°F)
K	-	time-constant ratio = T_1/T_2 (dimensionless)
k	-	thermal conductivity (Btu/hr-ft-°F)
N_{Re}	-	Reynolds number (dimensionless)
R	-	temperature-difference ratio = $(t - t_-)/(t_+ - t)$ (dimensionless)
T	-	temperature (°R), or time constant (sec; hr)
t	-	temperature (°F)
t'	-	temperature derivative = $dt/d\tau$ (°F/sec)
u	-	velocity (ft/hr)
V	-	velocity (ft/sec)
W	-	weight of thermocouple (lb)
ϵ	-	emissivity (dimensionless)
Θ	-	temperature ratio = $(t_g - t)/(t_g - t_i)$ (dimensionless)
ν	-	kinematic viscosity (ft^2/hr)
σ	-	Stefan-Boltzmann constant(Btu/hr-ft^2-°R^4)
τ	-	time (sec; hr)

<u>Subscripts</u>

1	-	hollow thermocouple
2	-	solid thermocouple
+	-	at time $(\tau + \Delta\tau)$
-	-	at time $(\tau - \Delta\tau)$
c	-	convective heat transfer
f	-	gas film on thermocouple surface
g	-	gas stream
i	-	initial (at $\tau = 0$)
o	-	reference thermocouple
r	-	radiant heat transfer
s	-	shield or surroundings

I. INTRODUCTION

This program is the second phase of an effort to prove the feasibility of a novel concept for measuring temperatures in the range 5,000 to 10,000°F, which are presently being generated in rockets, arc-heated plasmas, and advanced propulsion systems. Although knowledge of these temperatures is essential for a complete evaluation of the characteristics and performance of the systems, such temperatures are extremely difficult to measure. Furthermore, the problem is usually magnified by the large variations found in a given stream.

In the dual-element approach, the instantaneous stream temperature is inferred from simultaneous temperature-time measurements of two transducers of equal shape but unequal thermal capacity. Analytical studies under the previous contract indicated that the dual-element transducer is feasible and that it should be possible to provide accurate measurements where previously no measurements, or at best only poor ones, could be obtained (ref. 8). Since laboratory confirmation in that program was meager, more detailed experimental work was undertaken in the present program to prove the reliability of the concept.

Manuscript released March 1963 by the author for publication as an ARL Technical Documentary Report.

II. DISCUSSION

PRINCIPLE OF THE DUAL-ELEMENT TRANSDUCER

A Single Thermoelement in a Gas Stream

The output of a thermal transducer, such as a thermocouple or a resistance thermometer, placed in a hot stream will be a function of the stream temperature, the thermal capacity and geometry of the thermoelement, and the rates of convective and radiant heat exchange between the element and its surroundings. All of these quantities may change with time.

An instantaneous heat balance on such an element in a subsonic stream, as shown in Figure 1, yields

$$h_c A (t_g - t) + h_r A (t_s - t) = Wc\ dt/d\tau \ . \tag{1}$$

Eq (1) can be simplified either 1) when the temperature of the surroundings follows the temperature of the thermoelement and $(t_s - t) = 0$; or 2) when the temperature of the surroundings is equivalent to the gas temperature, t_g. Defining $h = h_c + h_r$ in either case, Eq (1) becomes

$$hA (t_g - t) = Wc\ dt/d\tau \tag{2}$$

If h were known in Eq (2), it would be possible to calculate t_g from measured values of t and $dt/d\tau$. Unfortunately, h is a complex function of the flow on the surface of the thermoelement and its value can only be estimated.

The time constant of the thermoelement is defined (ref. 1) as $T = Wc/hA$.

The Dual-Element Concept

The necessity of knowing h is eliminated in the dual-element transducer, shown schematically in Figure 2. Two thermoelements of the same outside diameter and area, A, given the same orientation to the gas stream, have the same heat-transfer coefficient, h. Their thermal capacities, however, differ. The elements in Figure 2 are made of the same materials, their difference in capacity resulting from making one hollow and one solid. This difference could also be achieved by using different materials for the two thermoelements.

Writing Eq (2) for the two thermoelements:

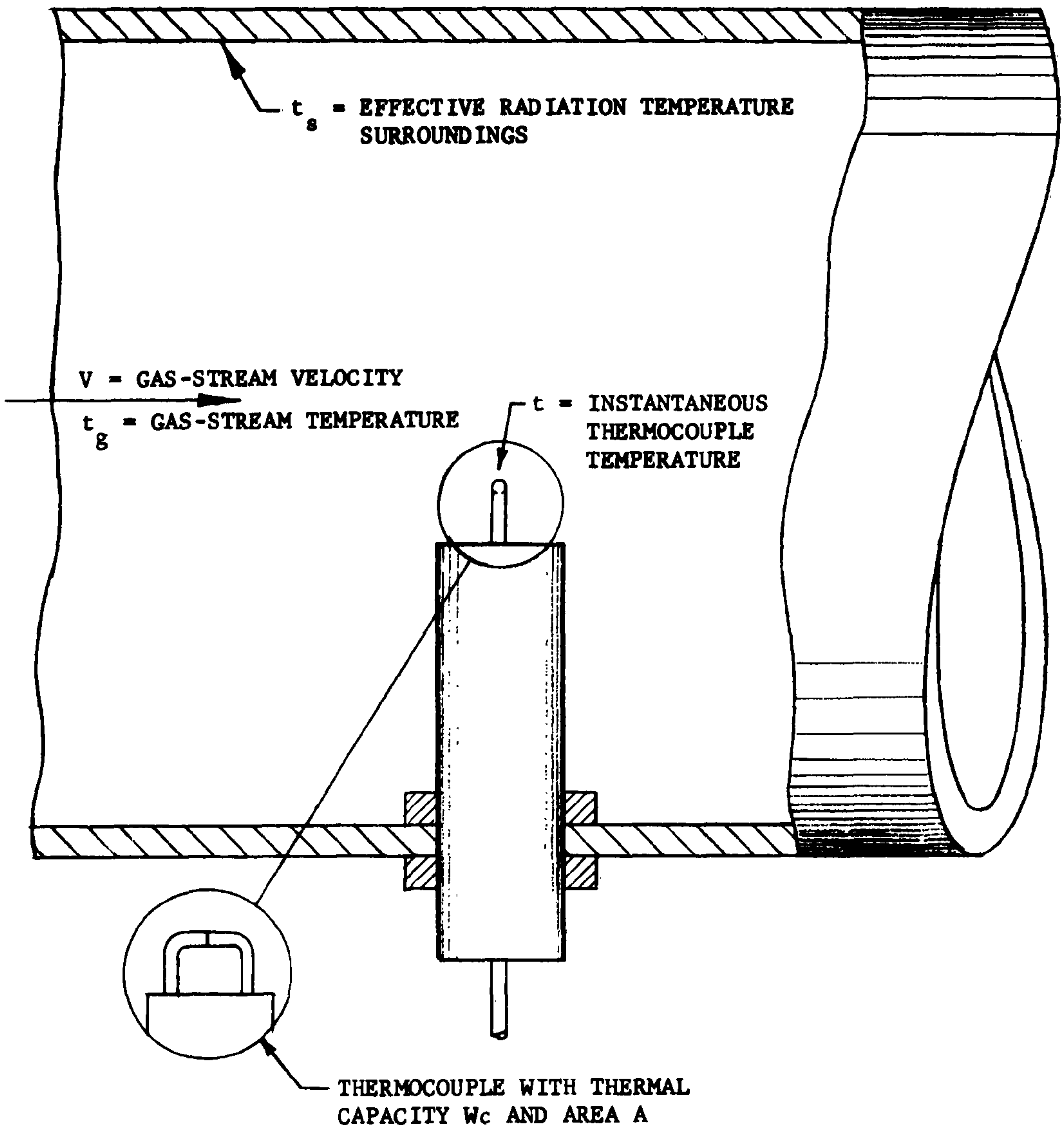
$$hA (t_g - t_1) = (Wc)_1\ dt_1/d\tau = (Wc)_1 t_1' \tag{4}$$

and

$$hA (t_g - t_2) = (Wc)_2\ dt_2/d\tau = (Wc)_2 t_2' \ . \tag{5}$$

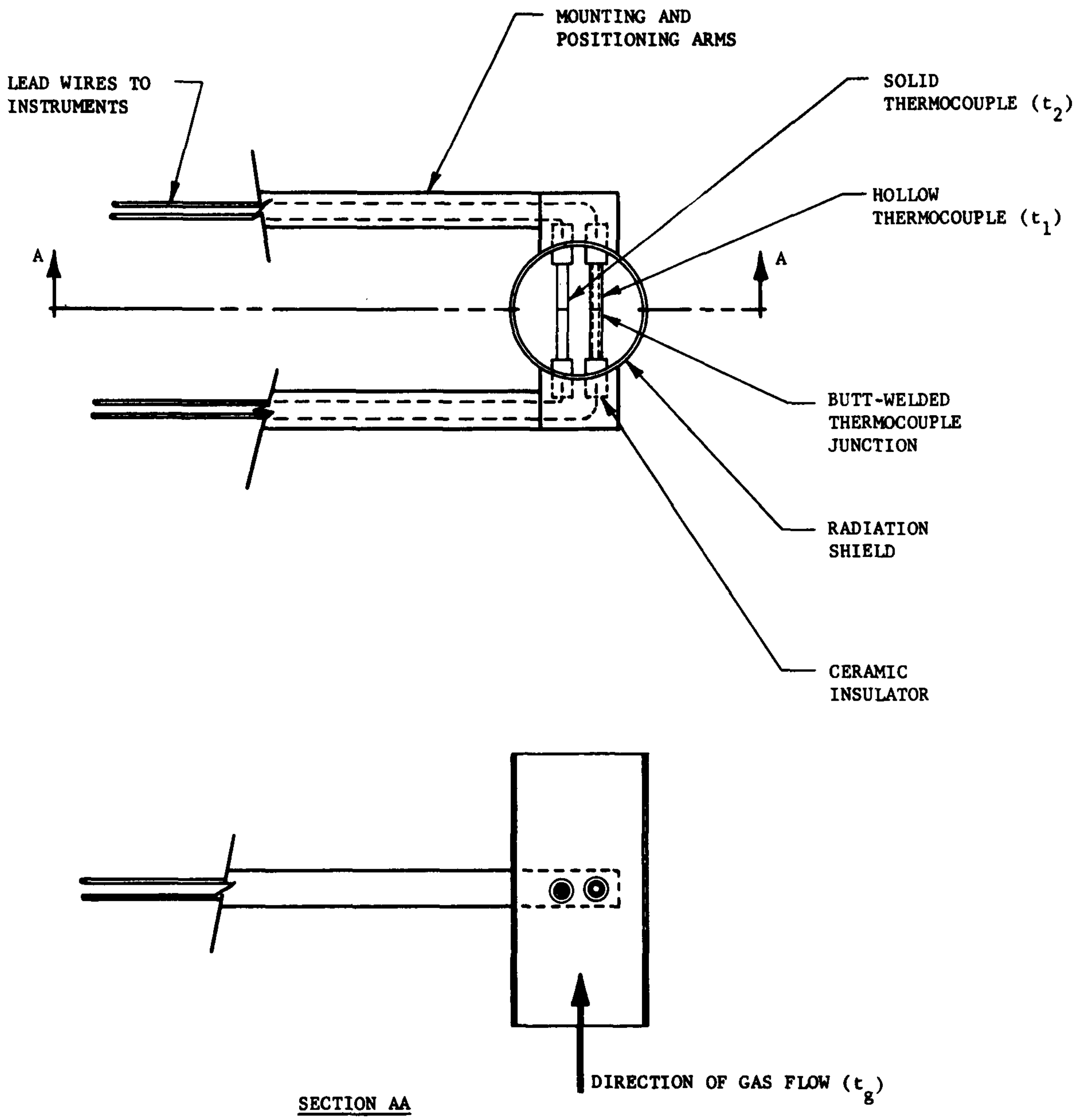
Eliminating hA, the common value,

$$t_g = \frac{t_1 - K \dfrac{t_1'}{t_2'} t_2}{1 - K \dfrac{t_1'}{t_2'}} \ , \tag{6}$$



THERMOELEMENT IN A GAS STREAM

FIGURE 1



SCHEMATIC VIEW OF DUAL-ELEMENT TRANSDUCER

FIGURE 2

where $K = (Wc)_1/(Wc)_2 = T_1/T_2$. It is evident that instantaneous values of t_g can be computed from temperature records of the two thermoelements.

Measurement of Temperature Distributions

Eq (4) and Eq (5) are instantaneous functions for the two thermoelements. The general result for the gas temperature, Eq (6), is thus equally applicable for computing a transient temperature or a steady temperature. The first case includes measuring the distribution of temperatures in a stream, where the ambient temperature of the transducer changes as a result of its travel across the stream.

It is interesting to note that, when the distribution of temperatures in the stream is steady, it is not necessary to pass the two elements through the stream simultaneously. It is necessary only that the response of each sensor as a function of position in the stream be known, and that the sensors traverse the same path through the stream at identical velocities.

Additional Applications

When the stream velocity is greater than about Mach 0.5, the recovery temperature begins to deviate from the free-stream temperature, t_g, of the gas (ref. 1). In other applications, it may not be possible to make the simplification for radiant exchange leading to Eq (2). It should still be possible to measure stream temperatures under these conditions using equations similar to Eq (6), although these relationships will be more complex.

ACCURACY OF THE DUAL-ELEMENT TRANSDUCER

It was concluded from an analytical study of the dual-element transducer (ref. 8) that an accuracy from ±6 to ±20% was probable in measuring subsonic gas temperatures in the vicinity of 4900°F. Attainment of the lower value (±6%) was dependent primarily on achieving maximum accuracy in evaluating the derivatives, t_1' and t_2', and the time constant ratio, K, in Eq (6).

The maximum accuracy resulted when the ratio, K, was not close to unity. In the approximate range $0 < K < 0.5$, the accuracy of the transducer was no longer affected by changes in the time-constant ratio.

The level of the gas temperature did not appear to have a strong effect on the transducer accuracy. In fact, decreased accuracy at lower temperatures seemed possible.

EVALUATION OF THE CONCEPT

Experimental Program

The purpose of the present contract was to confirm the reliability of the dual-element transducer as indicated by the studies of the preceding contract. The bulk of the laboratory investigation was performed over a range from 1500 to 2200°F, using an oxyacetylene apparatus available from the preceding contract. Additional testing was performed at about 5000°F in a second oxyacetylene apparatus available at ATL.

Design of the Transducer

The general design of the transducer shown in Figure 2 was adopted for the present program. Hollow and solid Chromel/Alumel thermocouples, fabricated from butt-welded cylinders, were selected as thermoelements because of the availability, reliability, and convenience of the materials and configuration.

Three separate thermocouple pairs were tested, having the dimensions shown in Table I. Pairs A and B had equal convective coefficients at the surface but differing values of K, while the reverse was true for pairs A and C. The dimensions shown for pair C represented the minimum hole size and wall thickness readily machinable on the 3/4-inch-long thermocouple.

The thermocouple pairs were fitted with Chromel and Alumel leads, alumina insulators, and a stainless-steel radiation shield; this assembly was mounted in a supporting arm made from square, stainless-steel tubing (refer to Figures 3, 4, and 5). The radiation shield was fabricated with the dimensions 0.750-inch OD by 0.010-inch wall by 2 inches long. This length and thickness were chosen to give an estimated average time constant of 2.5 seconds for the shield, resulting in a thermal response midway between the two thermocouples in pairs A and B. In this way, the radiant condition of $(t_s - t) = 0$ in the development of Eq (2) was approximated.

The thermocouple pairs were machined from butt-welded, 1/8-inch bar stock that was certified by the supplier to meet ISA special limits of accuracy (±3/8% maximum deviation from NBS tables over the range 530 to 2300°F). Because of the machining required, the thermoelements were recalibrated in the laboratory against laboratory standards after machining, but were found to be still within the above limits of accuracy.

Additional Apparatus

The mounting arm for the dual-element transducer was connected to a solenoid-actuated pneumatic cylinder (Figure 6). The velocity of injection was regulated by adjusting the pressure acting on the cylinder. In this way it was possible to 1) inject the assembly rapidly to the centerline of the gas stream, approximating a step change in the ambient temperature of the transducer; or 2) move the assembly through the stream at a slower, approximately constant velocity, exposing the transducer to the temperature variations within the stream.

The standard, or "true" temperature of the gas stream was obtained with the reference thermocouple shown in Figure 7. Static measurements (usually at the centerline of the stream) were made after the reference thermocouple had reached steady state. This thermocouple was provided with triple shielding to minimize radiation losses to the surroundings. The gas-stream temperature was obtained from reference-thermocouple measurements as detailed in Appendix A.

The static output from the reference thermocouple was obtained from a Leeds & Northrup Model 8662 millivolt potentiometer. Temperature histories from the dual-element transducer were recorded on a Minneapolis-Honeywell Model 1108 "Visicorder," equipped with Kintel Model 112A wideband dc amplifiers. The Visicorder was calibrated against the L & N potentiometer before each test. The attenuation of the thermocouple outputs was adjusted to make

TABLE I

THERMOCOUPLE PARAMETERS FOR DUAL-ELEMENT TRANSDUCER

Thermocouple Pair	Thermocouple 1 (Hollow Cylinder)				Thermocouple 2 (Solid Cylinder)			Time-Constant Ratio, K
	OD, d_o (in.)	ID, d_i (in.)	h (Btu/hr-ft^2-°F)	T_1 (sec)	OD, d_o (in.)	h (Btu/hr-ft^2-°F)	T_2 (sec)	
A	0.065	0.055	78.3[a]	1.04[b]	0.065	78.3[a]	3.65[c]	0.285[d]
B	0.065	0.043	78.3	2.05	0.065	78.3	3.65	0.562
C	0.051	0.043	82.1	0.795	0.051	82.1	2.74	0.290

a. Heat transfer coefficient on thermocouple surface estimated on basis of 1800°F air stream at velocity of 100 ft/sec.

b. Time constant, $T_1 = [Wc\, d_o/4h]\left(1 - \frac{d_i^2}{d_o^2}\right)$

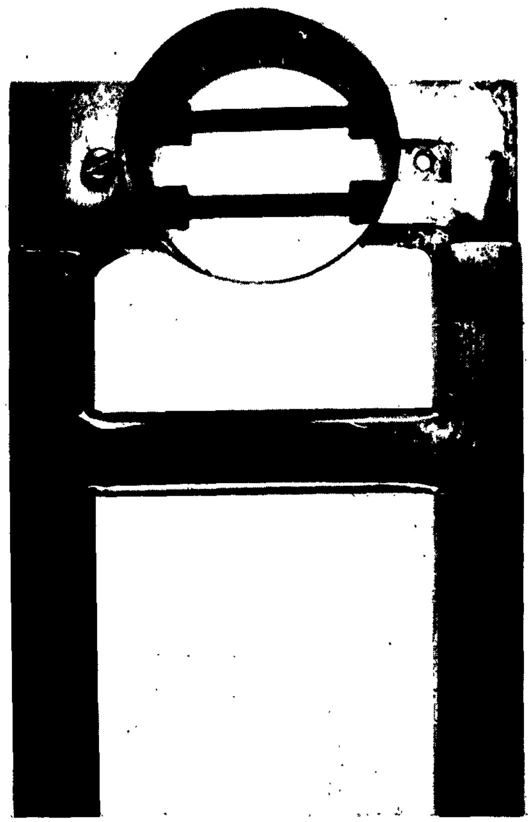
c. Time constant, $T_2 = Wc\, d_o/4h$.

d. $K = T_1/T_2 = \left(1 - \frac{d_i^2}{d_o^2}\right)$; independent of heat transfer coefficient and properties of materials.

A cylindrical Chromel/Alumel thermocouple with lead wires attached, two insulators, and a radiation shield are shown before assembly.

TRANSDUCER COMPONENTS

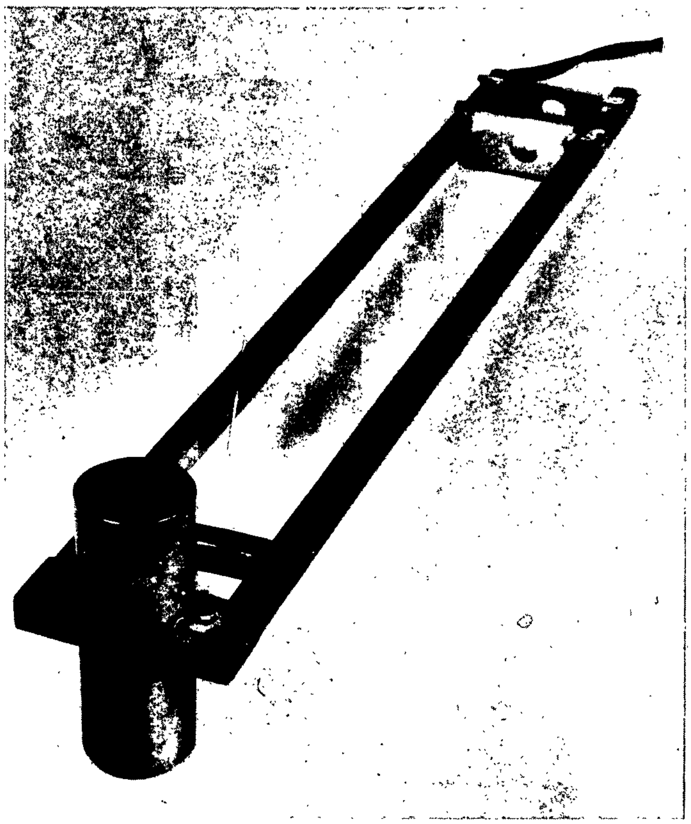
FIGURE 3



Chromel/Alumel thermocouple pair is shown installed with alumina insulators. Cover is removed from right side, exposing lead wires anchored with alumina cement.

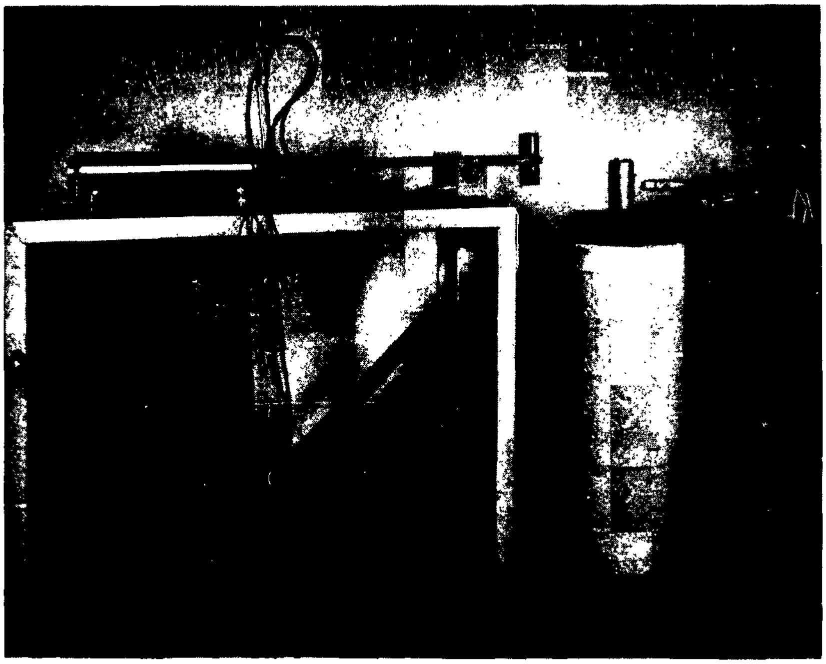
AXIAL VIEW OF DUAL-ELEMENT TRANSDUCER

FIGURE 4



OVER-ALL VIEW OF DUAL-ELEMENT TRANSDUCER

FIGURE 5



The dual-element transducer is shown attached to pneumatic cylinder for rapid injection over stream tube. The reference thermocouple is shown in position at the centerline of the stream tube. The stream tube is insulated with asbestos lagging, as used in testing thermocouple pairs A and C.

CLOSE-UP VIEW OF TEST STAND

FIGURE 6

2265

OVER-ALL VIEW OF REFERENCE THERMOCOUPLE

FIGURE 7

maximum use of the 8-inch chart width on the Visicorder, giving the maximum accuracy in reducing the records to temperature data.

The assembled test stand is shown in Figure 8, with the heating apparatus used for testing in the range 1500 to 2200°F. A close-up view of the oxyacetylene apparatus used for testing at approximately 5000°F is shown in Figure 9.

EXPERIMENTAL RESULTS

Verification of Time-Constant Ratio

As mentioned earlier, analysis of the probable accuracy of the transducer (ref. 8) indicated that errors in the value of K have a strong effect on the accuracy with which t_g can be computed from Eq (6). It was therefore considered essential to determine actual values of K experimentally, for comparison with the predicted values in Table I.

When the transducer is injected into the stream rapidly, a step increase in the ambient temperature of the transducer results. This condition is discussed in Appendix B. Eq (B-2), which applies, can be rearranged to define the dimensionless parameter, Θ, or

$$\Theta = \frac{t_g - t}{t_g - t_i} = 1 - \frac{t - t_i}{t_g - t_i} = e^{-\tau/T} \quad . \tag{7}$$

When the gas temperature, t_g, is known from the data, the experimental temperature data, t, can be expressed as Θ, which, when plotted as a function of time on semi-log paper, should result in a straight line. The initial (negative) slope of this line is the inverse of the time constant.

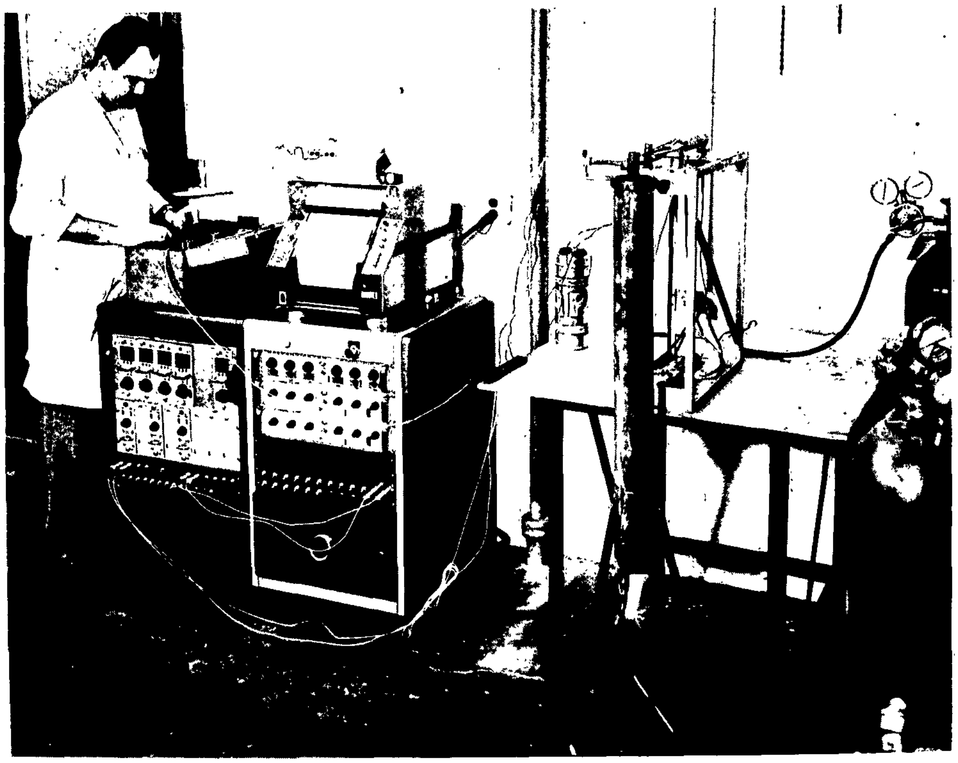
Three preliminary runs were made at low temperatures with thermocouple pair C, and the data were reduced to plot Θ as a function of time. The data from Run P-5 are given in Table II and plotted in Figure 10. The results of the three tests are shown in Table III; the average experimental value, K = 0.2905, is in agreement with the predicted value of 0.290 in Table I.

It was subsequently found that an experimental value of K could be obtained from tests in which t_g was not known, and that this value was also in agreement with Table I. Consequently, separate tests for the determination of the time-constant ratio were not made on thermocouple pairs A and B.

Gas-Temperature Constant: 1500 to 2300°F

A number of tests were made with thermocouple pairs A, B, and C in which the dual-element transducer was rapidly injected into the centerline of the stream with the apparatus shown in Figure 6. The data from six representative tests were reduced and are presented in Tables IV through IX.

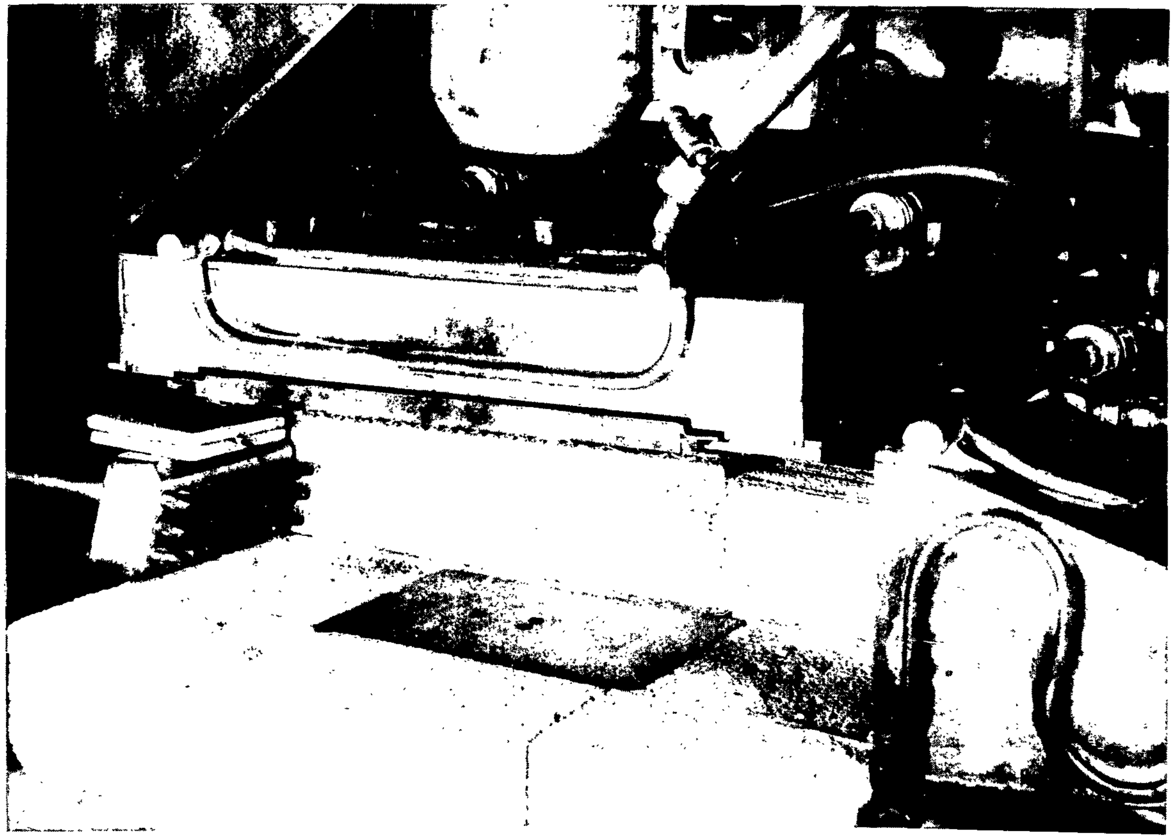
The first efforts to calculate derivatives from these data were based on tangents drawn to the temperature histories plotted on rectangular coordinates. A consistent value of the



Dual-element transducer shown connected to Visicorder, with reference thermocouple connected to potentiometer. Insulation removed from stream tube, as used in Runs B-1 and B-9.

OVER-ALL VIEW OF TEST STAND

FIGURE 8



Apparatus used in Runs B-13 and B-15 includes a 30-tip oxyacetylene torch supplied through flowmeters for close control of fuel-to-oxygen ratio. On the right is a water-cooled exhaust duct; the graphite radiation source above the test section was not operated during the tests.

CLOSE-UP VIEW OF 5000°F TEST STAND

FIGURE 9

TABLE II

EXPERIMENTAL VERIFICATION OF TIME-CONSTANT RATIO FOR THERMOCOUPLE PAIR C

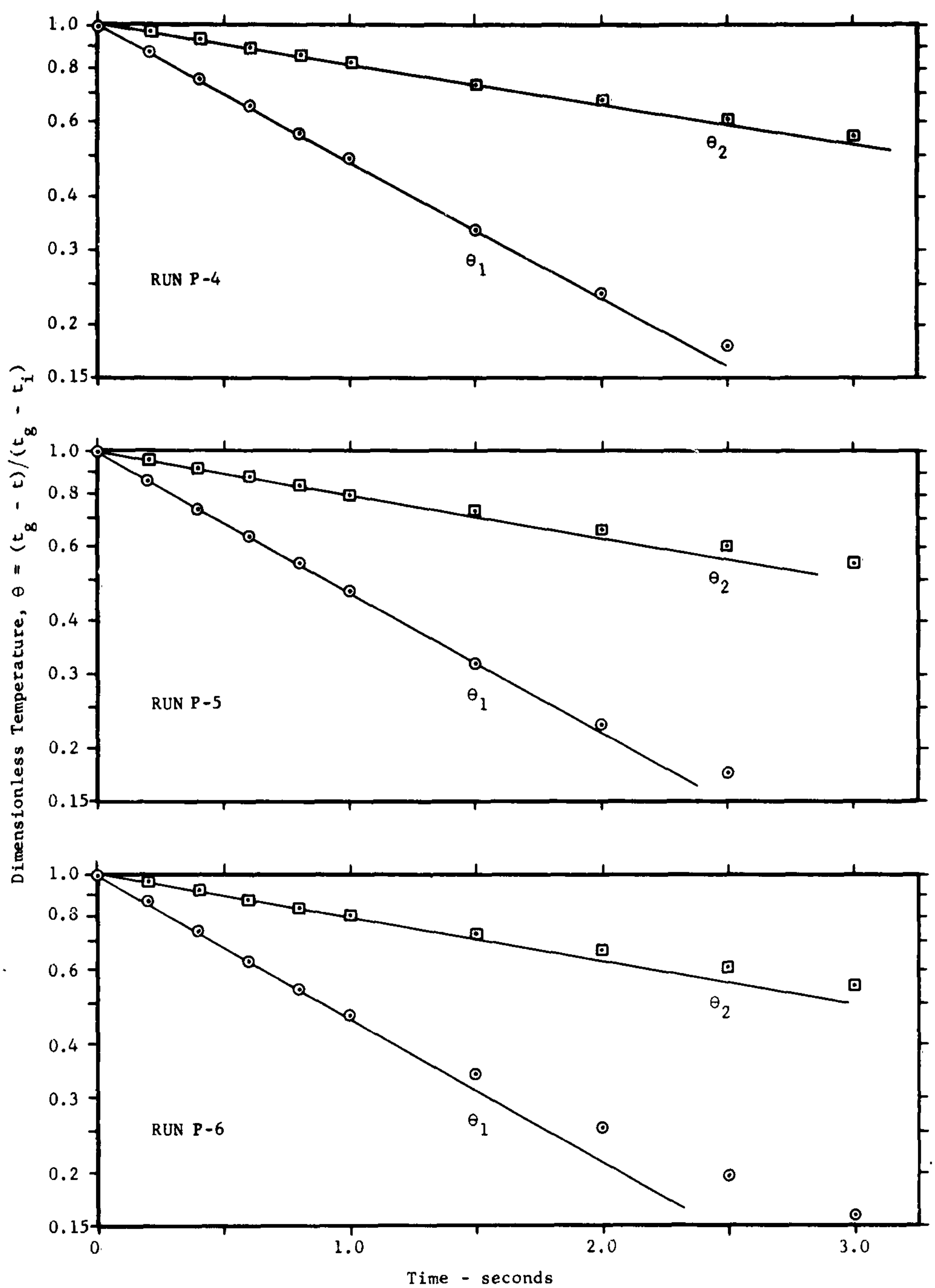
PRELIMINARY RUN P-5

Time (sec)	t_1 (°F)	$\frac{t_1 - t_i}{t_f - t_i}$	θ_1	t_2 (°F)	$\frac{t_2 - t_i}{t_f - t_i}$	θ_2
0	104	0	1.000	113	0	1.000
0.2	265	0.141	0.859	165	0.047	0.953
0.4	409	0.267	0.733	208	0.085	0.915
0.6	524	0.367	0.633	251	0.124	0.876
0.8	624	0.454	0.546	296	0.165	0.835
1.0	714	0.532	0.468	337	0.202	0.798
1.5	888	0.685	0.315	422	0.278	0.722
2.0	991	0.774	0.226	493	0.342	0.658
2.5	1051	0.827	0.173	563	0.405	0.595
3.0	1097	0.868	0.132	619	0.455	0.545
3.5	1131	0.898	0.102	675	0.506	0.494
4.0	1139	0.904	0.096	722	0.548	0.452
∞	1250	1.000	0	1224	1.000	0

TABLE III

COMPUTATION OF TIME CONSTANTS FOR THERMOCOUPLE PAIR C

	T_1 (sec)	T_2 (sec)	$K = T_1/T_2$
P-4	1.398	5.02	0.278
P-5	1.321	4.46	0.296
P-6	1.259	4.23	0.297
Avg.			0.2905



EXPERIMENTAL VERIFICATION OF
TIME-CONSTANT RATIO FOR THERMOCOUPLE PAIR C

FIGURE 10

2120

TABLE IV

EXPERIMENTAL DATA FROM RUN C-4

a. Dual-element Transducer Injected into Centerline of Gas Stream:

	Hollow Thermocouple, t_1				Solid Thermocouple, t_2					
Time	t	$(t - t_-)$	$\frac{t - t_-}{t_+ - t}$	t'^*	t	$(t - t_-)$	$\frac{t - t_-}{t_+ - t}$	t'^*	$\frac{t_1'}{t_2'}$	t_g
(sec)	(°F)	(°F)	—	(°F/sec)	(°F)	(°F)	—	(°F/sec)	—	(°F)
0	99.0			965**	99.3			280**	3.445+	
0.07	163.0				122.5					
0.37	399.0	236.0	1.280	692	200.0	77.5	1.122	244	2.835	1318
0.67	583.5	184.5	1.286	541	269.0	69.0	1.112	217.5	2.49	1402
0.97	727.0	143.5	1.304	421	331.0	62.0	1.118	195.3	2.155	1388
1.27	837.0	110.0	1.269	323	386.5	55.5	1.120	174.9	1.848	1356
1.57	923.7	86.7		254.5	436.0	49.5	1.112	156.0	1.631	1361
1.87	985.0	61.3			480.5	44.5				
2.17	1037.7	52.7			523.0	42.5				
2.47	1080.0	42.3			562.7	39.7				
Avg.			1.285				1.1168			1365

* $t_1' = 2.935\,(t_1 - t_-)$; $t_2' = 3.15\,(t_2 - t_-)$.

** Extrapolated from semi-log plot of derivatives.

+ $K = t_2'/t_1'$ at $\tau = 0$, or $K = 0.290$.

b. Reference Thermocouple at Centerline of Gas Stream:

Thermocouple temperature:	$t_o = 1476.5$°F
Shield temperature:	$t_s = 1393.7$°F
Gas velocity:	$V = 29.5$ ft/sec
Correction to thermocouple reading:	$(t_g - t_o) = 45.9$°F
Gas-stream temperature:	$t_g = 1522.4$°F
Probable error in gas temperature:	$\Delta t_g = \pm 16.0$°F

TABLE V

EXPERIMENTAL DATA FROM RUN C-5

a. Dual-element Transducer Injected into Centerline of Gas Stream:

	Hollow Thermocouple, t_1					Solid Thermocouple, t_2						
Time	t	$(t - t_-)$	$(t - t_-)^*$	$\frac{t - t_-}{t_+ - t}$	t'^{**}	t	$(t - t_-)$	$(t - t_-)^*$	$\frac{t - t_-}{t_+ - t}$	t'^{**}	$\frac{t_1'}{t_2'}$	t_g
(sec)	(°F)	(°F)	(°F)	—	(°F/sec)	(°F)	(°F)	(°F)	—	(°F/sec)	—	(°F)
0	130.0				962†	130.0				277†	3.47††	
0.09	211.0				890†	154.7				268†	3.32	1432
0.39	442.0	231.0	234.0	1.300	684	232.0				240†	2.845	1397
0.69	624.3	182.3	180.0	1.300	526	300.0	145.3	145.0	1.244	216.5	2.43	1386
0.99	769.0	144.7	138.5	1.294	404	363.5				193.5	2.085	1381
1.29	868.0	99.0	107.0	1.303	312.5	415.5	115.5	116.5	1.236	173.8	1.741	1328
1.59	949.0	81.0	82.0	1.294	239.5	464.0				156	1.535	1331
1.89	1014.5	65.5	63.3	1.299	185.0	510.3	94.8	94.3	1.241	140.8	1.313	1321
2.19	1063.0	48.5	48.7	1.294	142.2	549.7				126.5	1.123	1312
2.49	1101.0	38.0	37.6		109.9	586.7	76.4	76.0		113.4	0.969	1301
Avg.				1.298					1.2403			1354

* Adjusted to best straight line on semi-log graph.

** $t_1' = 2.92\ (t_1 - t_-)$; $t_2' = 1.492\ (t_2 - t_-)$.

† Extrapolated from semi-log plot of derivatives.

†† $K = t_2'/t_1'$ at $\tau = 0$, or $K = 0.288$.

b. Reference Thermocouple at Centerline of Gas Stream:

Thermocouple temperature:	$t_o = 1520.5$°F
Shield temperature:	$t_s = 1396.0$°F
Gas velocity:	$V = 32.5$ ft/sec
Correction to thermocouple reading:	$(t_g - t_o) = 64.0$°F
Gas-stream temperature:	$t_g = 1584.5$°F
Probable error in gas temperature:	$\Delta t_g = \pm 21.2$°F

TABLE VI

EXPERIMENTAL DATA FROM RUN C-7

a. Dual-element Transducer Injected into Centerline of Gas Stream:

	Hollow Thermocouple, t_1							Solid Thermocouple, t_2								
Time	t	$(t - t_-)$	$(t - t_-)^*$	t^{**}	$(t_+ - t)$	$\frac{t - t_-}{t_+ - t}$	$t'^{\dagger}$	t	$(t - t_-)$	$(t - t_-)^*$	t^{**}	$(t_+ - t)$	$\frac{t - t_-}{t_+ - t}$	$t'^{\dagger}$	$\frac{t_1'}{t_2'}$	t_g
(sec)	(°F)	(°F)	(°F)	(°F)	(°F)		(°F/sec)	(°F)	(°F)	(°F)	(°F)	(°F)		(°F/sec)		(°F)
0	110.0			110.0			1440	110.3			110.3			418	3.44††	
0.08	213.3			212.0	127.5		1320	144.0			143.5	39.7		406	3.25	1368
0.18	339.5	126.2	127.5	339.5	115.8	1.101	1215	185.0	41.0	39.7	183.2	38.1	1.041	390	3.12	2065
0.28	455.3	115.8	115.8	455.3	106.0	1.092	1102	222.5	37.5	38.1	221.3	36.7	1.039	374	2.95	1872
0.38	553.5	98.2	106.0	561.3	96.2	1.101	1010	258.0	35.5	36.7	258.0	35.3	1.040	360	2.80	1877
0.48	651.5	98.0	96.2	657.5	87.6	1.099	917	293.3	35.3	35.3	293.3	33.9	1.041	346	2.65	1883
0.58	736.0	84.5	87.6	745.1	80.0	1.095	835	325.5	32.2	33.9	327.2	32.6	1.040	333	2.51	1881
0.68	816.0	80.0	80.0	825.1	72.7	1.100	763	357.3	31.8	32.6	359.8	31.3	1.041	320	2.38	1870
0.78	888.7	72.7	72.7	897.8	66.0	1.101	693	387.0	29.7	31.3	391.1	30.0	1.042	307	2.26	1873
0.88	959.7	71.0	66.0	963.8	60.1	1.098	629	418.3	31.3	30.0	421.1	28.9	1.039	295	2.13	1850
0.98	1025.0	65.3	60.1	1023.9	54.5	1.102	573	448.5	30.2	28.9	450.0	27.8	1.040	284	2.02	1842
1.08	1078.0	53	54.5	1078.4				475.0	26.5	27.8	477.8	26.7	1.041	273		
1.18	1126	48						502.5	27.5	26.7	504.5	25.6	1.042	262		
1.28	1171	45						528.3	25.8	25.6	530.1	24.6	1.041	251.5		
1.38	1214	43						555.0	26.7	24.6	554.7	23.7	1.039	241.5		
1.48	1248	34						577.5	22.5	23.7	578.4	22.8	1.040	233		
1.58	1278	30						601.0	23.5	22.8	601.2					
Avg.						1.09880							1.04043			1876

* *Adjusted to best straight line on semi-log graph.*

** Adjusted to agree with $(t - t_-)$.

† $t_1' = 9.53\,(t_1 - t_-)$; $t_2' = 9.82\,(t_2 - t_-)$.

†† $K = t_2'/t_1'$ at $\tau = 0$, or $K = 0.2905$.

b. Reference Thermocouple at Centerline of Gas Stream:

Thermocouple temperature:	$t_o = 1855.5$°F
Shield temperature:	$t_s = 1685.3$°F
Gas velocity:	$V = 58.0$ ft/sec
Correction to thermocouple reading:	$(t_g - t_o) = 103.5$°F
Gas-stream temperature:	$t_g = 1959.0$°F
Probable error in gas temperature:	$\Delta t_g = \pm 33.7$°F

TABLE VII

EXPERIMENTAL DATA FROM RUN C-8

a. Dual-element Transducer Injected into Centerline of Gas Stream:

Time	Hollow Thermocouple, t_1: t	$(t - t_-)$ $\Delta\tau = 0.1$	$(t - t_-)$ $\Delta\tau = 0.2$	$(t - t_-)^*$ $\Delta\tau = 0.2$	$\frac{t - t_-}{t_+ - t}$	t'^{**}	Solid Thermocouple, t_2: t	$(t - t_-)$ $\Delta\tau = 0.1$	$(t - t_-)$ $\Delta\tau = 0.2$	$(t - t_-)$ $\Delta\tau = 0.3$	$(t - t_-)^*$ $\Delta\tau = 0.3$	$\frac{t - t_-}{t_+ - t}$	t'^{**}	$\frac{t_1'}{t_2'}$	t_g
(sec)	(°F)	(°F)	(°F)	(°F)		(°F/sec)	(°F)	(°F)	(°F)	(°F)	(°F)		(°F/sec)		(°F)
0	124.3					1720	125.0						503	3.42†	
0.01	126.5					1700	128.2						501	3.39	
0.11	292.0	165.5				1550	179.3	51.1					481	3.22	2060
0.21	436.5	144.5	310.0	309	1.201	1409	224.5	45.2	96.3				462	3.05	2150
0.31	570.5	134.0				1285	270.0	45.5		141.8	141.8	1 132	444	2 895	2210
0.41	692.0	121.5	255.5	257	1.200	1172	315.3	45.3	90.8				425	2.76	2255
0.51	807.5	115.5				1070	356.5	41.0					409	2.62	2260
0.61	909.0	101.5	217.0	214	1.201	977	395.5	39.0	80.2	125.5	125.5	1.131	391.5	2 495	2280
0.71	1004.0	95.0				890	435.0	39.5					374	2.38	2300
0.81	1084.0	80.0	175.0	178		812	471.0	36.0	75.5				360	2.255	2260
0.91	1158.0	74.0					507.3	36.3		111.8	111.8	1.136	346	2.14	2240
1.01	1218.0	60.0	134.0				541.0	33.7	70.0						
1.11	1271.0	53.0					572.3	31.3							
1.21	1322.5	51.5	104.5				605.3	33.0	64.3	98.0	98.0	1.131	304.5		
1.31							634.0	28.7							
1.41							662.0	28.0	56.7						
1.51							688.5	26.5		83.2	83.2	1.131	269		
1.61							713.7	25.2	51.7						
1.71							739.3	25.6							
1.81							764.0	24.7	50.3	75.5	75.8				
1.91							787.0	23.0							
2.01							811.0	24.0	47.0						
2.11							833.7	22.7		69.7					
2.21							855.5	21.8	44.5						
2.31							878.0	22.5							
2.41							897.0	19.0	41.5	63.3					
Avg.					1 2007							1.1322			2258††

* Adjusted according to Figures C-1 and C-2.

** t_1' 4.56 $(t_1 - t_-)$; t_2' 3.13 $(t_2 - t_-)$.

† K t_2'/t_1' at τ 0, or K 0.292.

†† Values at τ 0.11 and τ 0.21 excluded.

b. Reference Thermocouple at Centerline of Gas Stream:

Thermocouple temperature:	t_o = 2089 0°F
Shield temperature:	t_s = 1855.5°F
Gas velocity:	V = 110 ft/sec
Correction to thermocouple reading:	$(t_g - t_o)$ = 159.2°F
Gas-stream temperature:	t_g = 2248 2°F
Probable error in gas temperature:	Δt_g ± 52.1°F

TABLE VIII

EXPERIMENTAL DATA FROM RUN A-5

a. Dual-element Transducer Injected into Centerline of Gas Stream:

	Hollow Thermocouple, t_1				Solid Thermocouple, t_2					
Time	t	$(t - t_-)^*$	$\frac{t - t_-}{t_+ - t}$	$t_1'^{**}$	t	$(t - t_-)^*$	$\frac{t - t_-}{t_+ - t}$	$t_2'^{**}$	$\frac{t_1'}{t_2'}$	t_g
(sec)	(°F)	(°F)		(°F/sec)	(°F)	(°F)		(°F/sec)		(°F)
0	103.7			1050†	97.5			303†	3.48††	
0.08	193.0				124.0					
0.28	386.0	191.5	1.160	889	180.5	59.2	1.058	277.5	3.20	2745
0.48	559.0	165.0	1.158	766	236.5	56.0	1.072	262.5	2.92	2240
0.68	701.7	142.5	1.153	661	288.7	52.2	1.059	244.5	2.705	2145
0.88	825.0	123.5	1.161	573	338.0	49.3	1.069	231	2.48	2035
1.08	932.0	106.5		494	382.5	46.1	1.051	216	2.28	1975
1.28	1018.7				427.0	43.9	1.058	205.5		
1.48	1088.5				468.5	41.5		194.5		
Avg.			1.1580							2099‡

* Adjusted to best straight line on semi-log plot.

** $t_1' = 4.64\ (t_1 - t_-)$; $t_2' = 4.69\ (t_2 - t_-)$.

† Extrapolated from semi-log plot of derivatives.

†† $K = t_2'/t_1'$ at $\tau = 0$, or $K = 0.2875$.

‡ Value at $\tau = 0.28$ excluded.

b. Reference Thermocouple at Centerline of Gas Stream:

Thermocouple temperature:	$t_o = 1965.0$°F
Shield temperature:	$t_s = 1761.0$°F
Gas velocity:	$V = 82.5$ ft/sec
Correction to thermocouple reading:	$(t_g - t_o) = 135.9$°F
Gas-stream temperature:	$t_g = 2100.9$°F
Probable error in gas temperature:	$\Delta t_g = \pm 45.0$°F

TABLE IX

EXPERIMENTAL DATA FROM RUN B-1

Dual-element Transducer Injected into Centerline of Gas Stream:

Time	Hollow Thermocouple, t_1				Solid Thermocouple, t_2					
	t	$(t - t_-)$	$\frac{t - t_-}{t_+ - t}$	t_1' **	t	$(t - t_-)$ *	$\frac{t - t_-}{t_+ - t}$	t_2' **	$\frac{t_1'}{t_2'}$	t_g
(sec)	(°F)	(°F)		(°F/sec)	(°F)	(°F)		(°F/sec)		(°F)
0	236.0			912 †	234.5			531 †	1.718 ††	-
0.3	489.3	253.3	1.176	778	387.5	152.0	1.105	481	1.618	2135
0.6	705.0	215.7	1.172	662	525.0	137.5	1.105	435.5	1.520	2085
0.9	888.7	183.7	1.182	564	648.5	123.5	1.111	394	1.431	2100
1.2	1044.0	155.3		477	759.0	110.5	1.103	354.5	1.344	2175
1.5	1185.7				859.3	100.3	1.105	321.5		
1.8	1309.7				951.0	91.7		290.5		
Avg.			1.1767				1.1058			2124

* Adjusted to best straight line on semi-log plot.

** $t_1' = 3.070\ (t_1 - t_-)$; $t_2' = 3.165\ (t_2 - t_-)$.

† Extrapolated from semi-log plot of derivatives.

†† $K = t_2'/t_1'$ at $\tau = 0$, or $K = 0.582$.

Reference Thermocouple at Centerline of Gas Stream:

Thermocouple temperature:	$t_o = 2037.5°F$
Shield temperature:	$t_s = 1811.5°F$
Gas velocity:	$V = 95$ ft/sec
Correction to thermocouple reading:	$(t_g - t_o) = 155.1°F$
Gas-stream temperature:	$t_g = 2192.6°F$
Probable error in gas temperature:	$\Delta t_g = \pm 49.7°F$

stream temperature from Eq (6) could not be obtained by this method; in a preliminary run with pair C, random fluctuations in t_g of ±600°F resulted from Eq (6), when the reference temperature of the gas stream was measured at 1706°F. It was apparent from these large variations that an improved method was needed for evaluating derivatives.

A more systematic method for computing derivatives from the temperature data is described in detail in Appendix B. This method involves evaluation of the temperature increase of each thermocouple over fixed intervals of time. It has two definite advantages:

1) The temperature increase is a direct exponential function of time, while the temperature itself is not. This makes it possible to plot the increase over each increment, $\Delta\tau$, as a function of time on semi-log paper and to select the best straight line for the data. The consistency of the temperature data is thereby increased.

2) The temperature derivative is the product of a constant and the temperature increase. The calculation of the derivatives is therefore very simple.

It must be noted, however, that this method of calculating derivatives is applicable only when the dual-element transducer is exposed to a step change in ambient temperature (i.e., when it is rapidly positioned at some location in the stream), since only this exposure results in a simple exponential response.

The evaluation of derivatives in Tables IV through IX was performed by the above method. The temperature of the gas stream was calculated from Eq (6), and the reference value of the stream temperature is given in each case. A sample calculation for Run C-8 is carried out in detail in Appendix C.

Gas-Temperature Constant: 5000°F

The dual-element transducer with its injection assembly was moved to the higher temperature oxyacetylene apparatus shown in Figure 9. The flowmeters on the supply lines were adjusted to supply 310 ft^3/hr (STP) of both oxygen and acetylene to the torch, or a fuel-to-oxygen ratio of 1. Observation of the flame indicated that both mixing and combustion were completed about 2 inches downstream from the nozzle tips. Accordingly, the transducer was positioned with the thermocouples directly in the flame, $3\frac{1}{2}$ inches downstream from the tips, and with the centerline of the shield on the centerline of the torch.

Several runs were made in which the transducer was rapidly injected and withdrawn from the flame. Runs B-13 and B-15 were selected for reduction because the settings for chart speed and signal attenuation on the Visicorder appeared the most satisfactory from the records. The data from these two runs are presented in Tables X and XI, and the temperature records from Run B-15 are shown in Figure 11. The calculation of the flame temperature was performed as described in Appendix C.

It is evident that the static, reference thermocouple could not be used for a comparative measurement near 5000°F, but comparable measurements have been made in oxyacetylene flames at the University of California (ref. 7). The torch at the University was identical to that used by ATL and the flow controls were similar. Their measurements of temperature,

TABLE X

EXPERIMENTAL DATA FROM RUN B-13

Dual-element Transducer Injected into Centerline of Gas-Stream:

Time	Hollow Thermocouple, t_1				Solid Thermocouple, t_2					
	t	$(t - t_-)^*$ $\Delta\tau = 0.06$	$\frac{t - t_-}{t_+ - t}$	$t_1'^{**}$	t	$(t - t_-)^*$ $\Delta\tau = 0.06$	$\frac{t - t_-}{t_+ - t}$	$t_2'^{**}$	$\frac{t_1'}{t_2'}$	t_g
(sec)	(°F)	(°F)		(°F/sec)	(°F)	(°F)		(°F/sec)		(°F)
0	255.0	-		3730†	208.7	-		2130†	1.752††	
0.003	263.7	-			210.8	-				
0.023	338.0	-			253.5	-				
0.043	409.3	-			294.7	-				
0.063	480.0	217.0	1.080	3480	336.5	125	1.041	2035	1.710	6700
0.083	550.0	211.0	1.069	3385	377.0	123.5	1.047	2010	1.686	5160
0.103	617.0	207.7	1.078	3330	417.5	122	1.048	1985	1.678	5290
0.123	681.0	201.0	1.070	3225	455.3	120	1.043	1952	1.651	4500
0.143	742.7	197.5	1.071	3170	495.0	118	1.043	1920	1.650	4760
0.163	806.0	192.5	1.070	3085	532.3	116.5	1.040	1898	1.627	4400
0.183	867.0	188.0	1.074	3015	570.5	115	1.045	1871	1.610	4340
0.203	930.0	184.0	1.076	2950	607.0	113	1.042	1840	1.603	4450
0.223	987.0	180.0		2885	646.0	112				
0.243	1044.0	175.0		2805	683.0	110				
0.263	1101.0	171.0		2740	719.0	108.5				
Avg.			1.0735				1.0436			4700‡

* Adjusted to best straight line on semi-log plot.

** $t_1' = 16.03\ (t_1 - t_-)$; $t_2' = 16.28\ (t_2 - t_-)$.

† Extrapolated from semi-log plot of derivatives.

†† $K = t_2'/t_1'$ at $\tau = 0$, or $K = 0.571$.

‡ Value at $\tau = 0.063$ excluded.

TABLE XI

EXPERIMENTAL DATA FROM RUN B-15

Dual-element Transducer Injected into Centerline of Gas-Stream:

Time	Hollow Thermocouple, t_1				Solid Thermocouple, t_2					
	t	$(t - t_-)^*$ $\Delta\tau = 0.06$	$\frac{t - t_-}{t_+ - t}$	$t_1'^{**}$	t	$(t - t_-)^*$ $\Delta\tau = 0.06$	$\frac{t - t_-}{t_+ - t}$	$t_2'^{**}$	$\frac{t_1'}{t_2'}$	t_g
(sec)	(°F)	(°F)		(°F/sec)	(°F)	(°F)		(°F/sec)		(°F)
0	217.0	-		3570†	185.2			2020†	1.763††	
0.017	284.7	-			220.7					
0.037	352.0	-			260.0					
0.057	423.3	-			299.2					
0.077	489.0	207.5	1.052	3370	341.0	119	1.026	1958	1.721	6280
0.097	556.7	204	1.051	3315	377.0	118	1.027	1941	1.707	5670
0.117	622.3	200.5	1.055	3260	415.0	117	1.021	1925	1.692	5480
0.137	684.5	197	1.052	3200	457.5	116	1.019	1908	1.679	5100
0.157	751.3	194	1.054	3150	493.0	115	1.019	1891	1.665	5020
0.177	814.0	190	1.050	3090	531.2	114.5	1.022	1882	1.641	4570
0.197	874.3	187	1.050	3040	569.7	114	1.028	1876	1.621	4280
0.217	935.0	184		2990	606.0	113		1859	1.609	4300
0.237	995.5	181		2940	644.0	112		1842	1.595	4310
0.257	1052.5	178		2890	680.0	111		1827	1.581	4360
0.357	1329.0				859.3					
0.457	1520.5				987.0					
0.557	1487.5				974.5					
0.657	1448.0				964.0					
Avg.			1.0520				1.0231			4789‡

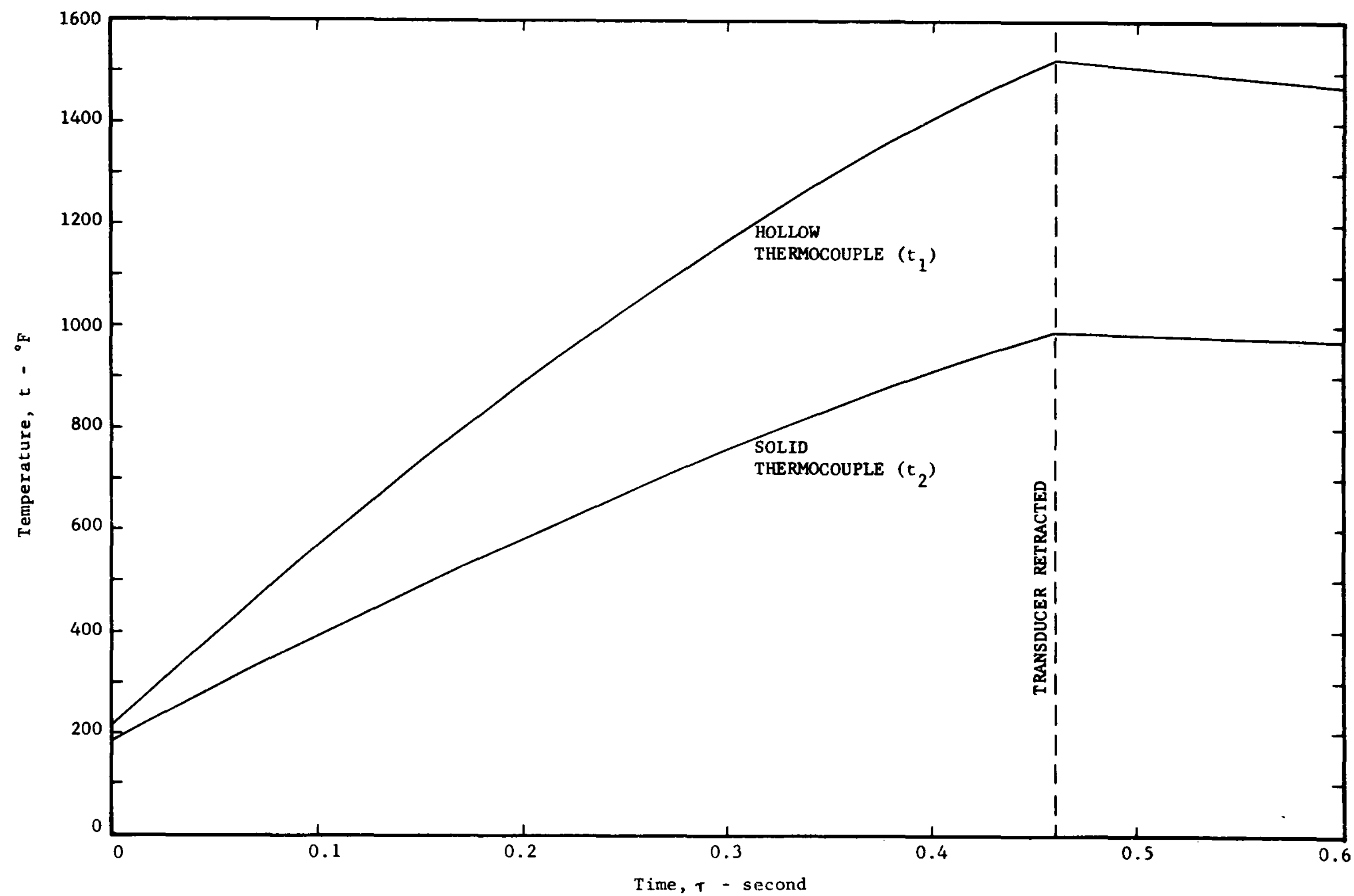
* Adjusted to best straight line on semi-log paper.

** $t_1' = 16.26\ (t_1 - t_-)$; $t_2' = 16.45\ (t_2 - t_-)$.

† Extrapolated from semi-log plot of derivatives.

†† $K = t_2'/t_1'$ at $\tau = 0$, or $K = 0.566$.

‡ Value at $\tau = 0.077$ excluded.



DUAL-ELEMENT TRANSDUCER RECORD IN 5000°F FLAME
(DATA FROM TABLE XI, RUN B-15)

FIGURE 11

made by the sodium-line-reversal technique at locations downstream from the tip and at a fuel-to-oxygen ratio of 1.0, are shown in Figure 12, where they are compared to the results obtained in Tables X and XI.

Measurement of Temperature Distribution

The low-temperature apparatus shown in Figure 8 was used to demonstrate the application of the transducer to measurement of transient temperatures. A traverse of half the diameter of the gas stream was selected, with the transducer coming to rest at approximately the centerline. The pressure on the pneumatic cylinder was adjusted for a traverse velocity of approximately 1.8 in./sec, since this resulted in a maximum thermocouple temperature of about 1200°F at the centerline. Radiation losses were thus minimized throughout the traverse.

The motion of the transducer was found to be approximately linear over the region of primary interest, i.e., the region of maximum temperature change near the wall. To establish the relation of position and time to the temperature of the thermocouples, the shaft on a linear potentiometer was attached to the transducer arm. With a second resistor and a battery in series, the voltage drop across the potentiometer was statically calibrated as a function of transducer position. After calibration, the transient voltage drop was recorded simultaneously with the thermocouple outputs on the Visicorder.

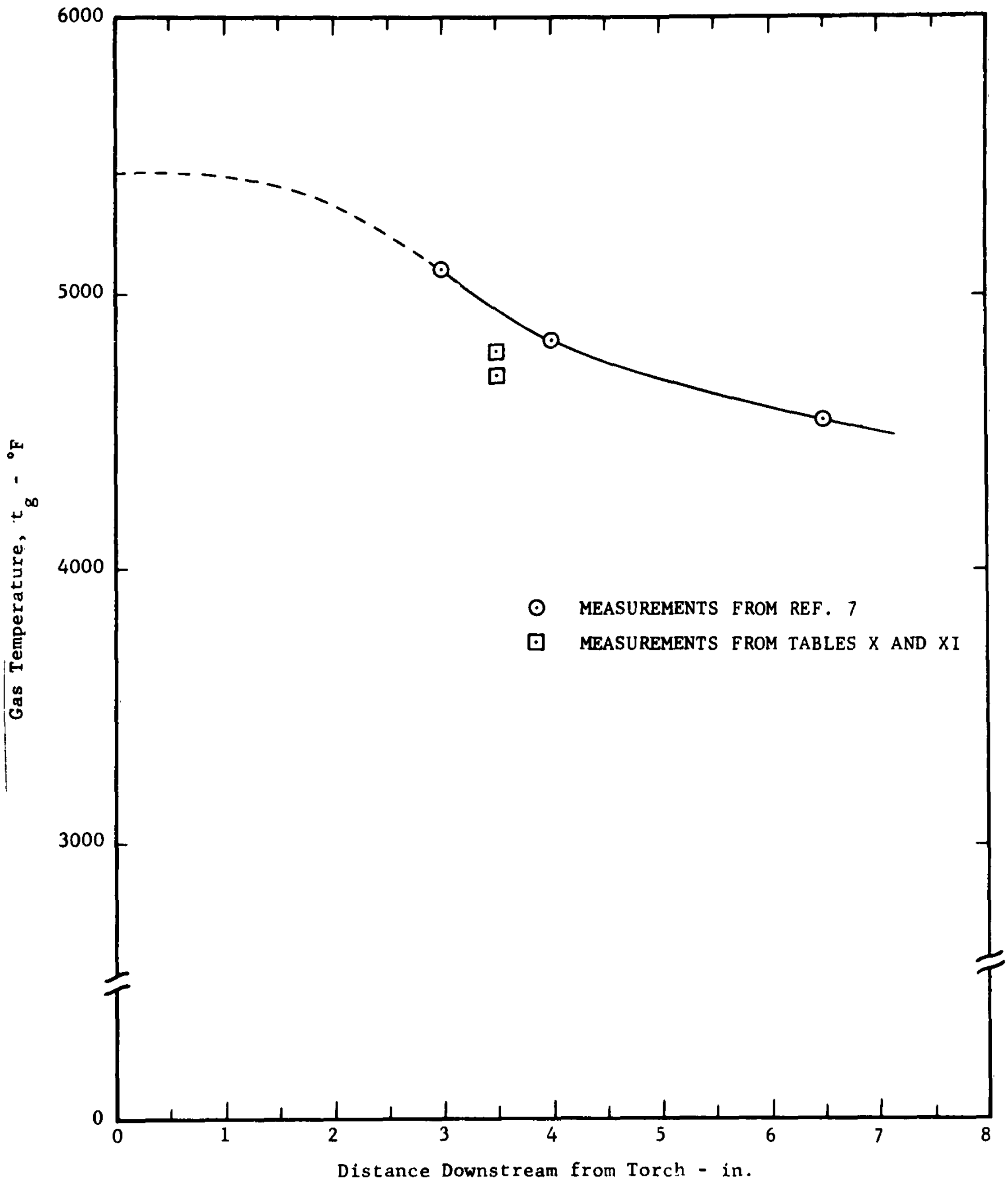
Table XIIa contains the data from Run B-9. The data from the two thermocouples were reduced as a function of true time indicated on the Visicorder record. By evaluating temperature increases over time increments of 0.2 second, it was found that the hollow and solid thermocouples entered a region of approximately constant gas temperature at about 1.3 and 1.7 seconds, respectively. This was indicated by a transition from nonlinearity to linearity when the temperature increases were plotted on semi-log paper. Beyond this time, derivatives were evaluated according to the constant-temperature method in Appendix C.

The derivatives during the earlier time of changing temperature were evaluated from tangents drawn to the temperature records plotted on rectangular coordinates. The slope method proved satisfactory in this case because the slopes changed rapidly in this region.

The centerlines of the two thermocouples (ref. Figure 4) are $\frac{1}{4}$ inch apart. From the position record, it was determined that the hollow thermocouple preceded the solid thermocouple by 0.14 second in the region of changing temperature. Accordingly, the data from the solid thermocouple in Table XIIa were displaced to coincide with the position of the hollow thermocouple, and the gas temperatures were calculated from Eq (6). The results are shown in Figure 13.

Static measurements of the stream temperature were made with the reference thermocouple at a number of points across the radius before the transducer traverse was made. After the traverse, an additional reference measurement was made at the centerline. These results are shown in Table XIIb, and it is noted that the stream temperature apparently decreased 180°F between reference measurements.

A Chromel/Alumel thermocouple was peened to the inside wall at the upstream end of the pipe to further define the temperature distribution.



TEMPERATURE IN OXYACETYLENE FLAME
DOWNSTREAM FROM 30-TIP TORCH

FIGURE 12

TABLE XII

EXPERIMENTAL DATA FROM RUN B-9

a. Dual-element Transducer Traversing Gas Stream:

Time	Position of t_1 with Respect to Pipe Wall	Hollow Thermocouple, t_1: t	Hollow Thermocouple, t_1: $(t - t_-)^*$ $\Delta\tau = 0.2$	Hollow Thermocouple, t_1: t_1'	Solid Thermocouple t_2: t	Solid Thermocouple t_2: $(t - t_-)^{**}$ $\Delta\tau = 0.2$	Solid Thermocouple t_2: t_2'	t_2 Adjusted to Correspond to Position of t_1: Time	t_2 Adjusted: $t_2^{\dagger\dagger}$	t_2 Adjusted: $t_2'^{\dagger\dagger}$	$\frac{t_1'}{t_2'}$	$t_g^{\ddagger}$
(sec)	(in.)	(°F)	(°F)	(°F/sec)	(°F)	(°F)	(°F/sec)	(sec)	(°F)	(°F/sec)		(°F)
0	-1.54	262.5		0	264.5		0	0.14	264.5	0	-	-
0.1	-1.34	262.5		0	264.5		0	0.24	264.5	0	-	-
0.2	-1.16	262.5		0	264.5		0	0.34	264.5	0	-	-
0.3	-0.96	264.0		$22.0^{\dagger}$	264.5		0	0.44	264.5	0	-	-
0.4	-0.86	267.3		39.3	264.5		0	0.54	264.5	0	-	-
0.5	-0.73	272.0		47.9	264.7		0	0.64	269	97	0.494	274
0.6	-0.47	282.5		267	265.0		$53.7^{\dagger}$	0.74	293	318	0.840	273
0.7	-0.26	330.0		540	281.5		216.5	0.84	332	408	1.322	323
0.8	-0.04	394.5		625	315.6		405	0.94	373	408	1.531	533
0.9	+0.08	459.0		654	357.0		410	1.04	414	402	1.627	975
1.0	+0.25	522.5		651	396.0		409	1.14	454	397	1.639	1384
1.1	0.42	586.0		639	438.0		403	1.24	493	389	1.631	1692
1.2	0.60	649.3		620	476.5		399	1.34	531	381	1.628	2002
1.3	0.89	711.5	125.5	596^{*}	517.3		390	1.44	569	372	1.601	2045
1.4	1.03	768.3	119	566	554.0		382	1.54	607	362	1.562	1985
1.5	1.10	824.5	113	537	592.6		371	1.64	643	351	1.530	1990
1.6	1.12	875.3	107	513	627.0		359	1.74	677	341	1.504	2000
1.7	1.13	928.0	102	485	664.5	71.9	347.5^{**}	1.84	711	330	1.470	1995
1.8	1.14	974.5	98.0	466	696.5	69.2	334.5	1.94	743	320	1.458	2060
1.9	1.15	1021.0	93.0	442	731.3	67.0	324	2.04	775	309	1.431	2065
2.0	1.22	1063.0	88.0	418	762.0	65.0	314	2.14	805	299	1.399	2040
2.1	1.38	1105.3	83.5	397	793.6	62.9	304	2.24	835	289	1.373	2045
2.2	1.39	1143.0	80.0	380	822.3	60.7	293.5	2.34	863	279	1.362	2080
2.3	1.41	1181.5	76.0	358	851.0	58.7	284	2.44	890	271	1.321	2050
2.4	1.42	1215.0	71.5	339	879.5	56.9	275	2.54	917	262	1.294	2030
2.5	1.57	1249.0	68.0	323	905.5	55.0	266	2.64	942	253	1.278	2045
2.6	1.70	1279.3	65.5	311	932.0	53.2	257	2.74	967	247	1.260	2055
2.7	1.78	1310.5	62.0	294	957.5	51.6	249.5	2.84	991	238	1.236	2050
2.8	1.81	1338.5			981.5	49.8	240.5					
2.9	1.82	1368.0			1006.0	48.2	233					
3.0	1.82	1394.5			1028.0	46.8	226					

TABLE XII
(concluded)

b. Reference Thermocouple Measurements:

Position with Respect to Pipe Wall (in.)	Thermocouple Temperature, t_o (°F)	Shield Temperature, t_s (°F)	Gas Velocity, V (ft/sec)	Correction to Thermocouple Reading, $(t_g - t_o)$ (°F)	Gas-Stream Temperature, t_g (°F)	Probable Error, Δt_g (°F)
		Before Dual-Element Transducer Traverse				
0.03	1712.5	1562.5	48.5	93.2	1805.7	±30.4
0.28	1857.3	1649.5	66	133.0	1990.3	±42.9
0.53	1940.7	1731.5	77.5	140.2	2080.9	±45.4
0.78	2009.0	1790.0	90	147.0	2156.0	±47.3
1.03	2036.3	1812.0	95	151.1	2187.4	±48.6
1.28	2040.0	1811.5	96	155.5	2195.5	±50.3
1.53‡‡	2020.0	1797.7	92	153.9	2173.9	±49.7
		After Dual-Element Transducer Traverse				
1.53‡‡	1854.5	1667.0	66	140.2	1994.7	±45.2
		Thermocouple Attached to Pipe Wall				
0	756.0					

Notes: * $(t - t_-)/(t_+ - t)$ avg. $= 1.1059$; $t_1' = 4.75\ (t_1 - t_-)$.

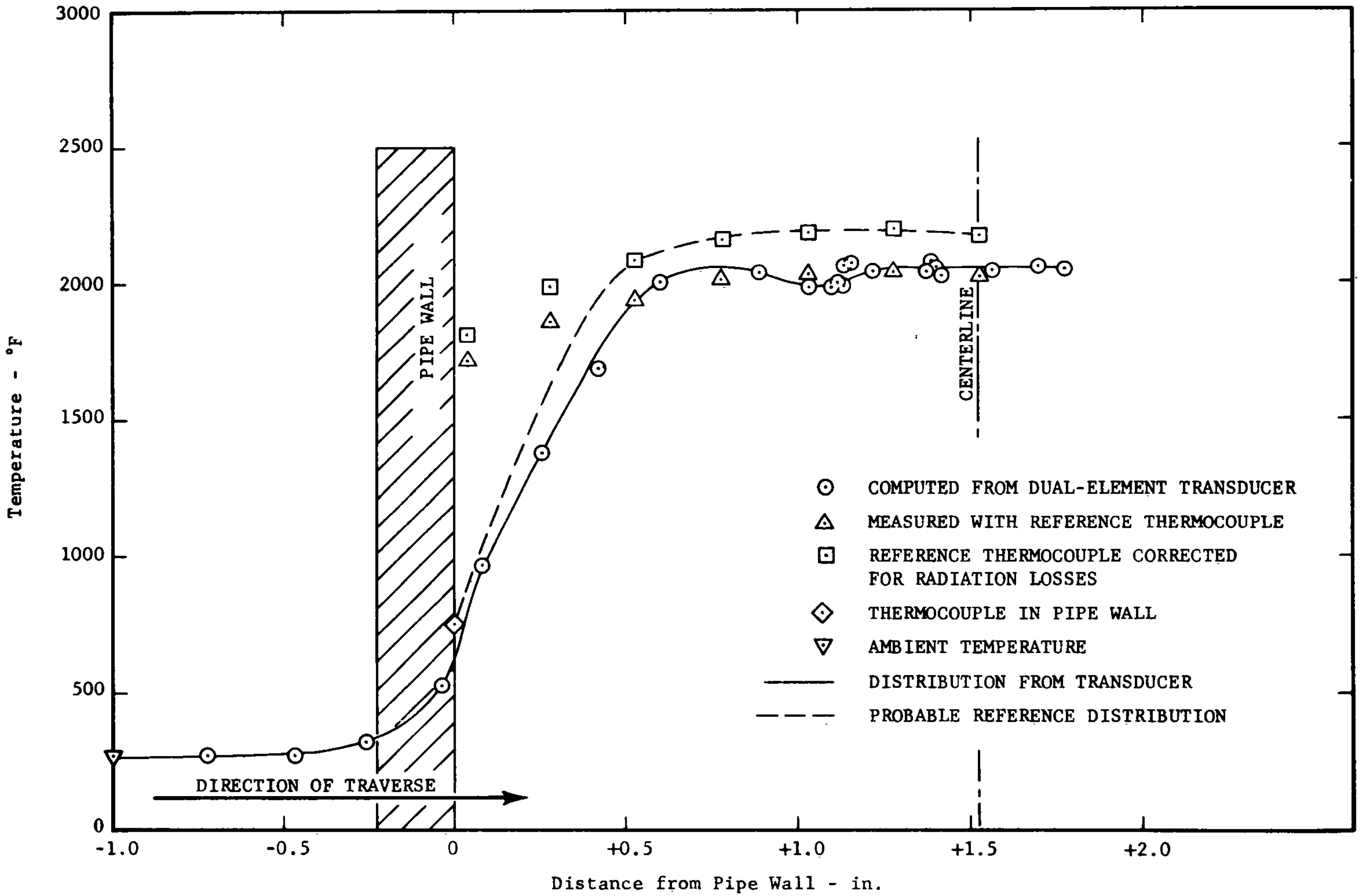
** $(t - t_-)/(t_+ - t)$ avg. $= 1.0687$; $t_2' = 4.83\ (t_2 - t_-)$.

† Evaluated from tangents drawn to temperature history.

†† Evaluated by interpolation from preceding data.

‡ Evaluated using K = 0.565.

‡‡ At centerline.



TEMPERATURE DISTRIBUTION IN GAS STREAM
MEASURED WITH DUAL-ELEMENT TRANSDUCER
(DATA FROM TABLE XII, RUN B-9)

FIGURE 13

DISCUSSION OF RESULTS

Steady Measurements

A summary of the results obtained with the dual-element transducer in measuring steady gas temperatures is given in Table XIII. The accuracy was within ±6% for measurements between 1950 and 2250°F. The error increased to ±15% in measuring gas temperatures in the region of 1500°F.

These values agree closely with the experimental accuracy predicted in the preceding analytical study (ref. 8). It is believed that agreement within ±6% of the standard temperature was made possible by the systematic method of calculating derivatives, a fact which was also predicted by the previous study.

The increasing error at 1500°F resulted primarily from the design of the transducer. The response of the thermocouples was slow, making the calculation of derivatives difficult even with the method outlined in Appendix C. It is believed that the accuracy could have been improved by using faster responding thermoelements; the region of 1500°F, however, was not of primary interest in this program.

It was noted in reducing the data that thermocouple pairs A and C produced more consistent results than did pair B. This, of course, results from the greater difference in time constants, T_1 and T_2, in pairs A and C. The ratio of the derivatives, t_1'/t_2', in Eq (6) is directly related to the ratio, $K = T_1/T_2$; the calculation was improved when the derivative ratio was larger.

The results of the measurements at 4700°F are considered excellent, both in the consistency of the transducer measurements and in the agreement of the measurements with published values. It is noted that the transducer accuracy falls within the ±6% that characterized the measurements from 1950 to 2250°F. The difference between the measurements at ATL and the published measurements by the sodium-line-reversal technique (ref. 7) are probably within the accuracy of the latter method.

It is especially important to note the fact illustrated in Figure 11. An excellent temperature measurement was made in a 4700°F flame from a record only 0.46 second long, in which the temperature of the thermoelements did not exceed 1500°F. This fact alone demonstrates the power of the dual-element concept.

Again the responses of the particular thermocouples created some difficulty. It is believed that better data in the region of 5000°F would result through the use of thermocouples with both higher individual time constants (i.e., slower response) and more widely separated time constants (i.e., a value for K of about 0.3).

An additional problem will be noted in the data in Tables X and XI. The calculated gas temperature appeared to decrease with time, although the consistency of the derivatives indicated that the measured gas temperature remained constant. This problem is believed to be related to the poor agreement in the initial temperatures of the two thermocouples, but

TABLE XIII

SUMMARY OF RESULTS WITH DUAL-ELEMENT TRANSDUCER

Run	Reference Temperature* (°F)	Probable Error in Reference Temperature (%)	Temperature from Dual-Element Transducer (°F)	Transducer Accuracy** (%)
C-4	1522	± 1.05	1365	-10.3
C-5	1585	± 1.34	1354	-14.5
C-7	1959	± 1.72	1876	- 4.2
C-8	2248	± 2.32	2258	+ 0.45
A-5	2101	± 2.14	2099	- 0.01
B-1	2193	± 2.27	2124	- 3.1
B-9†	2174	± 2.29	2050	- 5.7
B-13	4940††	± 3.0‡	4700	- 4.9
B-15	4940††	± 3.0‡	4789	- 3.1

* From reference thermocouple, except Runs B-13 and B-15.

** Based on reference temperature as standard.

† At centerline.

†† From ref. 7, as shown in Figure 12.

‡ As estimated in ref. 7.

sufficient time did not remain in the program to explore the matter fully. Again this problem was a matter of equipment design; the transducer could not be completely retracted from the region influenced by the flame.

Transient Measurements

The transient measurement in Figure 13 shows encouraging agreement with the probable reference values. The agreement within 6% at the centerline agrees with the centerline accuracy in previous measurements.

The derivatives in the region of changing temperature could not be calculated by the method in Appendix C. The slope method proved satisfactory in this case, however, because the slopes changed rapidly in this region. Satisfactory accuracy was obtained to demonstrate the applicability of the dual-element transducer in measuring transient temperatures.

There was, however, considerable ambiguity in establishing the true distribution through the stream. It is believed that the rather massive reference thermocouple did not make an adequate measurement near the wall for two reasons: 1) the outside diameter of 1 inch makes a point measurement impossible in a region with a large temperature gradient, and 2) the system of shield tended to conduct heat from the hotter region and influence the primary thermocouple. The wall thermocouple has been given greater credence in Figure 13, although this value too may be dubious.

While the distribution calculated from the transducer appears reasonable, it is evident that more definitive work is needed in this area. Further effort is necessary in developing an accurate method of evaluating derivatives in regions of changing temperature. In this instance particularly, coupling the dual-element transducer with digital or analog computation of derivatives would be advantageous.

III. CONCLUSIONS AND RECOMMENDATIONS

Experimental evaluation of the dual-element transducer has indicated accuracies well within ±6% in measuring constant gas-stream temperatures in the range 1950 to 2250°F. This is the maximum accuracy predicted in an earlier study (ref. 8), and is made possible by an accurate method developed for determining temperature derivatives. It is concluded that the feasibility of the concept has been demonstrated.

Measurements with the transducer in an oxyacetylene flame near 5000°F have demonstrated the feasibility of that application also. This temperature was evaluated from records in which the temperature of the thermoelements did not exceed 1500°F. The accuracy of the measurement appeared to be within the accuracy of values published elsewhere (ref. 7).

Limited experimental work has demonstrated the probability of using the dual-element transducer to measure temperature variations within a gas stream at about 2000°F. Again, the profile measured by the transducer appeared to be within the accuracy to which the actual profile was established.

It is strongly recommended that the evaluation and development of the dual-element transducer be continued. The results indicate that, with minor design changes, the transducer in its present state of development can be applied to the measurement of steady temperatures of the order of 5000°F. Evaluation of this application should be continued.

Additional evaluation of the transducer in measuring transient temperatures is needed. Coupling the transducer with data handling by either digital or analog computation is particularly attractive in this application, to bring the results to their maximum accuracy.

Finally, based on the extremely encouraging results of this program, it is recommended that evaluation of the dual-element transducer in measuring the ultra-high temperatures of plasma states be undertaken.

IV. REFERENCES

1. W. H. Giedt, Principles of Engineering Heat Transfer, New York, Van Nostrand (1957).

2. A. Hald, Statistical Theory with Engineering Applications, New York, John Wiley and Sons (1952).

3. I. Hilsenrath and Y. S. Touloukian, "The Viscosity, Thermal Conductivity, and Prandtl Number for Air, O_2, N_2, NO, H_2, CO, CO_2, H_2O, He, and A," Trans. ASME, 76, August 1954, p 967.

4. W. H. McAdams, Heat Transmission, Third Edition, New York, McGraw-Hill Book Co. (1954), p 76.

5. Ibid, p 475.

6. Ibid, p 260.

7. E. J. Russ, Heating Rate Characteristics of an Oxyacetylene Flame Apparatus for Surface Ablation Studies, University of California at Berkeley, Institute of Engineering Research, Report No. 128-3, December 1959.

8. M. I. Temme and W. H. Giedt, Dual Probe for High-Tempera.ure-Gas Measurements, Aeronautical Research Laboratory Report ARL 174, December 1961.

V. APPENDIX A

REFERENCE TEMPERATURE OF GAS STREAM

THE REFERENCE THERMOCOUPLE

The reference thermocouple was used for static measurements of the gas stream. The primary thermocouple was positioned at the center of three 2-inch-long stainless-steel shields with outside diameters by wall thicknesses of 1.000 by 0.049, 0.688 by 0.035, and 0.375 by 0.035 inch. Two additional thermocouples were spot-welded to the inner shield. All thermocouples were made from 10-mil Chromel/Alumel thermocouple wire certified by the supplier to meet ISA special limits of error (±3/8% maximum deviation from NBS tables over the range 530 to 2300°F).

The triple shielding was designed to minimize the radiation loss from the reference thermocouple, since this loss results in a depression of the thermocouple temperature below the true temperature of the gas stream. The depression was not completely eliminated, however, making it necessary to estimate the difference between the true gas temperature and the measured thermocouple temperature.

DETERMINATION OF THE GAS-STREAM TEMPERATURE

Assuming that the reference thermocouple radiates heat primarily to the inner shield, a heat balance on the thermocouple is:

$$t_g = t_o + \frac{\sigma F}{h} \left(T_o^4 - T_s^4\right). \tag{A-1}$$

The geometrical factor of the thermocouple with respect to the shield is $F'_{os} = 0.93$ (calculated as that portion of the radiation emitted by the thermocouple that is intercepted by the shield). Again assuming the inner shield primarily influences the thermocouple, the combined geometrical and emissivity factor from the blackened thermocouple is (ref. 4):

$$F = \frac{1}{1/F'_{os} - (1 - 1/\epsilon_o)} = 0.888, \tag{A-2}$$

where the value $\epsilon_o = 0.95$ is representative of oxidized Nichrome wire (ref. 5).

The thermocouple can be represented adequately for convection calculations as a small cylinder normal to the gas stream; therefore, for air with $40 < N_{Re} < 4000$ (ref. 6),

$$h = B\frac{k_f}{d} \left(\frac{ud}{\nu_f}\right)^{0.466}, \tag{A-3}$$

with the constant (ref. 6) $B = 0.615$.

Data on the high-temperature properties of air can be correlated in the range $1500 < T < 2700$°R by (ref. 3):

$$k_f = 4.46 \times 10^{-4}\, T_f^{0.59} \text{ and} \tag{A-4}$$

$$\nu_f = 0.798\, T_f^{0.741} , \tag{A-5}$$

and these values also approximate those for O_2, CO, CO_2, N_2, and water vapor (ref. 3).

Substituting the above values, and the relationship u = 3600V, the equation for the gas temperature becomes

$$t_g = t_o + 0.396 \frac{\sigma F T_f^{0.151} d^{0.534}}{B V^{0.466}} (T_o^4 - T_s^4). \tag{A-6}$$

Since the dependence of T_f on T_g implies a trial-and-error solution of Eq (A-6), the approximation is made that $T_f = 1.03\, T_o \pm 3\%$.

The velocity of the hot stream was based on wind-gage measurements of the gas flowing from the unlighted torch, corrected for expansion due to heating.

ACCURACY OF THE GAS-STREAM TEMPERATURE

The probable deviation in computing the correction $(t_g - t_o)$ is defined by (ref. 2):

$$\Delta(t_g - t_o) = \pm \sqrt{\sum_i \left[\frac{\partial (t_g - t_o)}{\partial x_i} \Delta x_i\right]^2} , \tag{A-7}$$

where x_i represents the seven "variables" in Eq (A-6). Evaluating the partial derivatives, the percentage deviation in the correction is defined by

$$\left[\frac{\Delta(t_g - t_o)}{(t_g - t_o)}\right]^2 = \left[\frac{4}{1 - (T_s/T_o)^4} \frac{\Delta T_o}{T_o}\right]^2 + \left[\frac{4}{(T_o/T_s)^4 - 1} \frac{\Delta T_s}{T_s}\right]^2$$
$$+ \left[\frac{\Delta F}{F}\right]^2 + \left[0.151 \frac{\Delta T_f}{T_f}\right]^2 + \left[0.534 \frac{\Delta d}{d}\right]^2$$
$$+ \left[\frac{\Delta B}{B}\right]^2 + \left[0.466 \frac{\Delta V}{V}\right]^2 . \tag{A-8}$$

The probable deviation in the computed gas-stream temperature is

$$\Delta t_g = \pm \sqrt{\left[\Delta t_o\right]^2 + \left[\Delta(t_g - t_o)\right]^2} . \tag{A-9}$$

The following deviations in the variables are representative:

1) $\Delta T_o = \pm 0.00375\ t_o$ and $T_s = \pm 0.00375\ t_s$, representing the limits of accuracy of the thermocouple wire specified by the supplier.

2) $\Delta F = \pm 0.05$.

3) $\Delta T_f = \pm 0.03 T_f = \pm 0.031 T_o$.

4) $\Delta d = \pm 0.001$ inch, when $d = 0.020$ inch.

5) $\Delta B = \pm 0.30B$, representing a deviation in the data from a number of investigators of approximately ±30% from the mean convection relationship expressed by Eq (A-3) (ref. 6).

6) $\Delta V = \pm 0.20V$.

Using typical data from Run C-8 ($T_o = 2549°R$, $T_s = 2316°R$, and $V = 110$ ft/sec):

$$\frac{\Delta(t_g - t_o)}{(t_g - t_o)} = \pm \sqrt{(14.7 + 6.57 + 25.0 + 0.21 + 7.11 + 900 + 86.8) \times 10^{-4}}$$

$$= \pm 0.323, \tag{A-10}$$

where the terms are given in the same order as in Eq (A-8). The error from the assumption for T_f is negligible. The uncertainty in the convection coefficient (represented by ΔB) obscures all other errors, indicating that further refinement in such measurements as V was unwarranted.

When the values $B = 0.615$, $d = 1.67 \times 10^{-3}$ ft, $F = 0.888$, $\sigma = 0.1713 \times 10^{-8}$ Btu/hr-ft^2-°R^4, and $T_f = 1.03\ T_o$ are substituted into Eq (A-6), the correction to the reference-thermocouple measurement can be estimated from

$$(t_g - t_o) = 32.3 \times 10^{-8} \frac{T_o^{0.131}}{V^{0.466}} (T_o^4 - T_s^4) . \tag{A-11}$$

VI. APPENDIX B

CALCULATION OF DERIVATIVES FOR CONSTANT GAS TEMPERATURE

ANALYSIS

In most of the experimental work, the dual-element transducer was rapidly injected into the centerline of the gas stream. In other words, for $\tau > 0$, the gas-stream temperature was constant. Eq (1) or (2) can be integrated for this condition, yielding

$$\ln (t_g - t) = -\frac{\tau}{T} + C, \tag{B-1}$$

where $T = Wc/hA$. The constant, C, is determined by noting that $t = t_i$ at $\tau = 0$, or

$$t = t_g - (t_g - t_i)\, e^{-\tau/T} \ . \tag{B-2}$$

The derivative is

$$t' = \frac{1}{T} (t_g - t_i)\, e^{-\tau/T} \ . \tag{B-3}$$

The derivatives were evaluated for this case of constant gas-stream temperature by a method represented in Figure B-1. The thermocouple temperature was evaluated from the experimental data at constant time increments, $\Delta\tau$. The time, τ, represents the point at which the derivative is to be evaluated; the temperatures one increment back (t_-) and one increment forward (t_+) are also used.

From Eq (B-2),

$$t_- = t_g - (t_g - t_i)\, e^{-(\tau - \Delta\tau)/T} \ . \tag{B-4}$$

The differences $(t - t_-)$ and $(t_+ - t)$ are:

$$(t - t_-) = (t_g - t_i)\, e^{-\tau/T} (e^{\Delta\tau/T} - 1) \ . \tag{B-5}$$

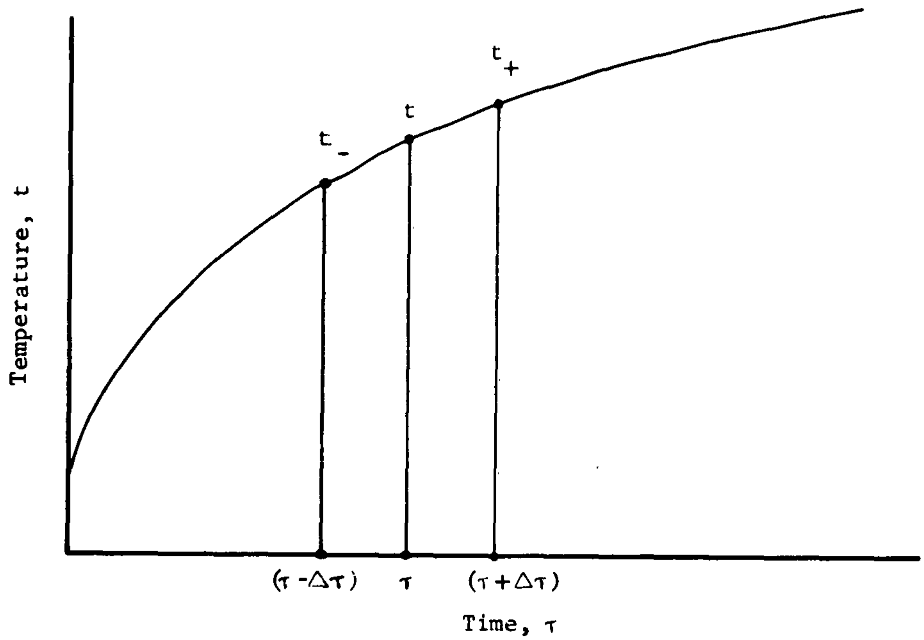
$$(t_+ - t) = (t_g - t_i)\, e^{-\tau/T} (1 - e^{-\Delta\tau/T}) \ . \tag{B-6}$$

The ratio of these differences (defined as R) is:

$$R = \frac{t - t_-}{t_+ - t} = \frac{e^{\Delta\tau/T} - 1}{1 - e^{-\Delta\tau/T}} = e^{\Delta\tau/T} \ . \tag{B-7}$$

Substituting Eq (B-5) and Eq (B-7) into Eq (B-3), the derivative is given by:

$$t' = \frac{\ln R}{\Delta\tau\,(R - 1)} (t - t_-) \ . \tag{B-8}$$



EVALUATION OF TEMPERATURE DATA
AT CONSTANT TIME INCREMENTS, $\Delta\tau$

FIGURE B-1

DATA-REDUCTION METHOD

The following points can be noted in the foregoing analysis:

1) The value of $\Delta\tau/T$ is constant for any given thermocouple.

2) The difference $(t - t_-)$ is an exponential function of time (since $\Delta\tau/T$ is constant) during the interval in which Eq (B-2) applies. The differences $(t - t_-)$ can therefore be plotted versus time on semi-log paper and faired to the best straight line.

3) The differences $(t_+ - t)$ have the same numerical values as $(t - t_-)$, displaced one interval, $\Delta\tau$, since they are evaluated from the same data.

4) The ratio $R = (t - t_-)/(t_+ - t)$ is a constant as long as Eq (B-2) applies.

5) The derivative (t') in Eq (B-8) is the product of a constant and the difference $(t - t_-)$.

This method has been followed in reducing the data included in this report. In computing the derivatives, the mean value of the constant, R, has been used in Eq (B-8).

VII. APPENDIX C

CALCULATION PROCEDURE FOR RUN C-8

DUAL-ELEMENT TRANSDUCER

The temperature histories for Run C-8 are shown in Table VII as obtained from Visicorder records. The temperature differences, $(t - t_-)$, are computed from the experimental data and plotted in Figures C-1 and C-2. The interval of the subtraction, $\Delta\tau$, was varied in this set of data, and it was noted that the consistency of the temperature differences increases as the interval increases.

An interval of 0.3 second was selected for further calculation. The best straight line was drawn through the plotted points, and the temperature differences were adjusted accordingly in Table VII. When the constant ratio, $R = (t - t_-)/(t_+ - t)$, was evaluated and averaged for each thermocouple, the derivatives were computed from Eq (B-8) for $\Delta\tau = 0.3$ second. The derivatives were also plotted in Figures C-1 and C-2 and were extrapolated to $\tau = 0$.

It will be noted from Eq (B-3) that the ratio of the temperature derivatives of the two thermocouples should equal the time-constant ratio initially, or

$$t_2'/t_1' = T_1/T_2 = K \text{ at } \tau = 0. \tag{C-1}$$

This ratio has a value of 0.292 for Run C-8, which agrees with the predicted value in Table I. The gas-stream temperature is calculated from Eq (6) in Table VII, using K = 0.292; the average value is $t_g = 2258°F$.

It will be noted that the data points for the hollow and solid thermocouples begin to deviate from the best straight lines at about 0.7 and 1.9 seconds, respectively. The deviations, however, occur in opposite directions because of the design of the transducer. Since the thickness of the radiation shield was chosen to make its thermal response midway between that of the two thermocouples, it can be assumed that the hollow, or faster responding thermocouple is losing heat to the radiation shield while the solid, slower responding thermocouple is gaining heat from the shield.

REFERENCE THERMOCOUPLE

The reference value of the gas temperature at the centerline of the stream was calculated, using the values $T_o = 2549°R$, $T_s = 2316°R$, and V = 110 ft/sec from Table VII, as follows:

$$(t_g - t_o) = 159.2°F \tag{A-11}$$

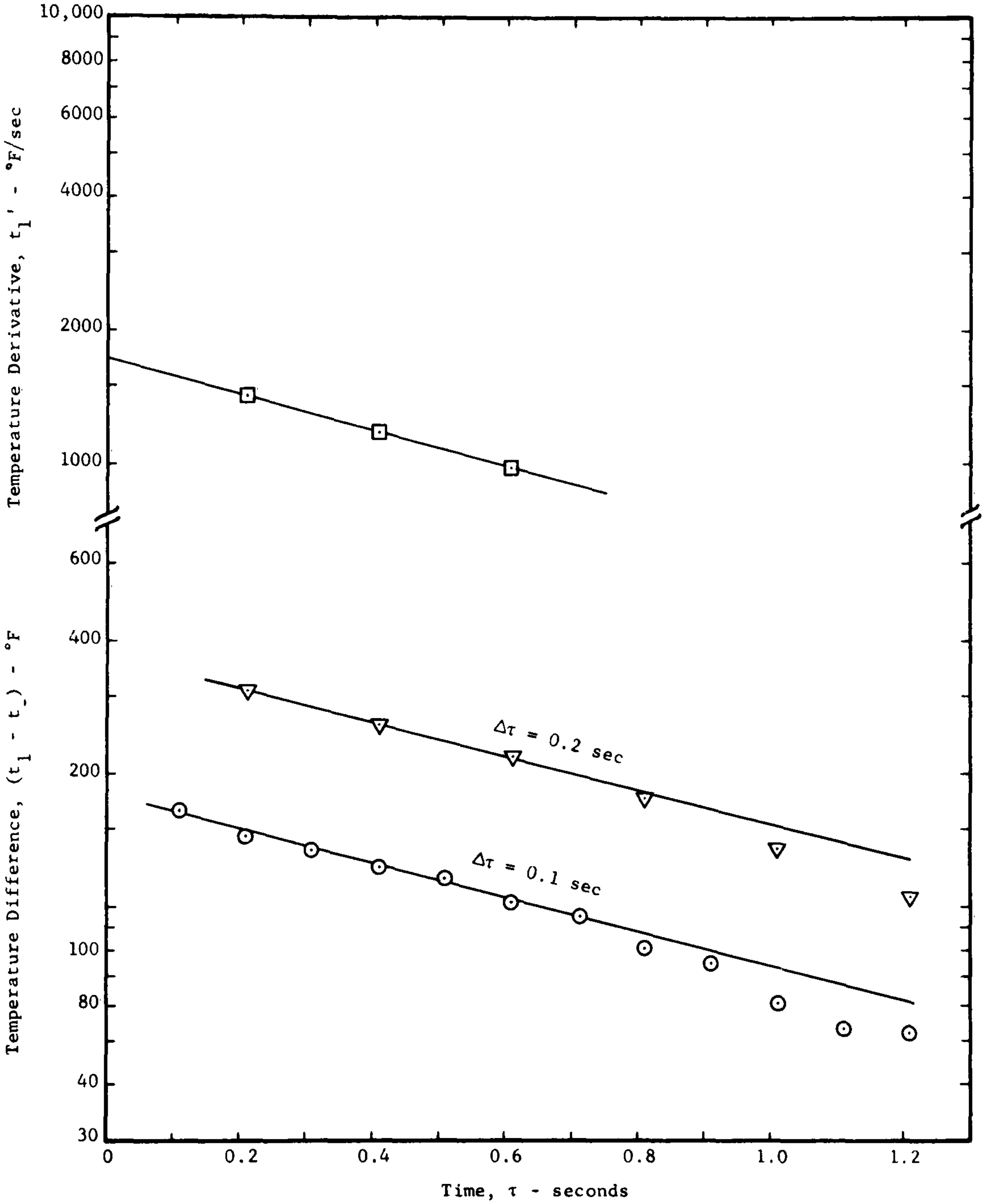
$$t_g = 2248.2°F$$

$$\Delta(t_g - t_o) = \pm\ 51.5°F \tag{A-10}$$

$$\Delta t_g = \pm \ 52.1°F \tag{A-9}$$

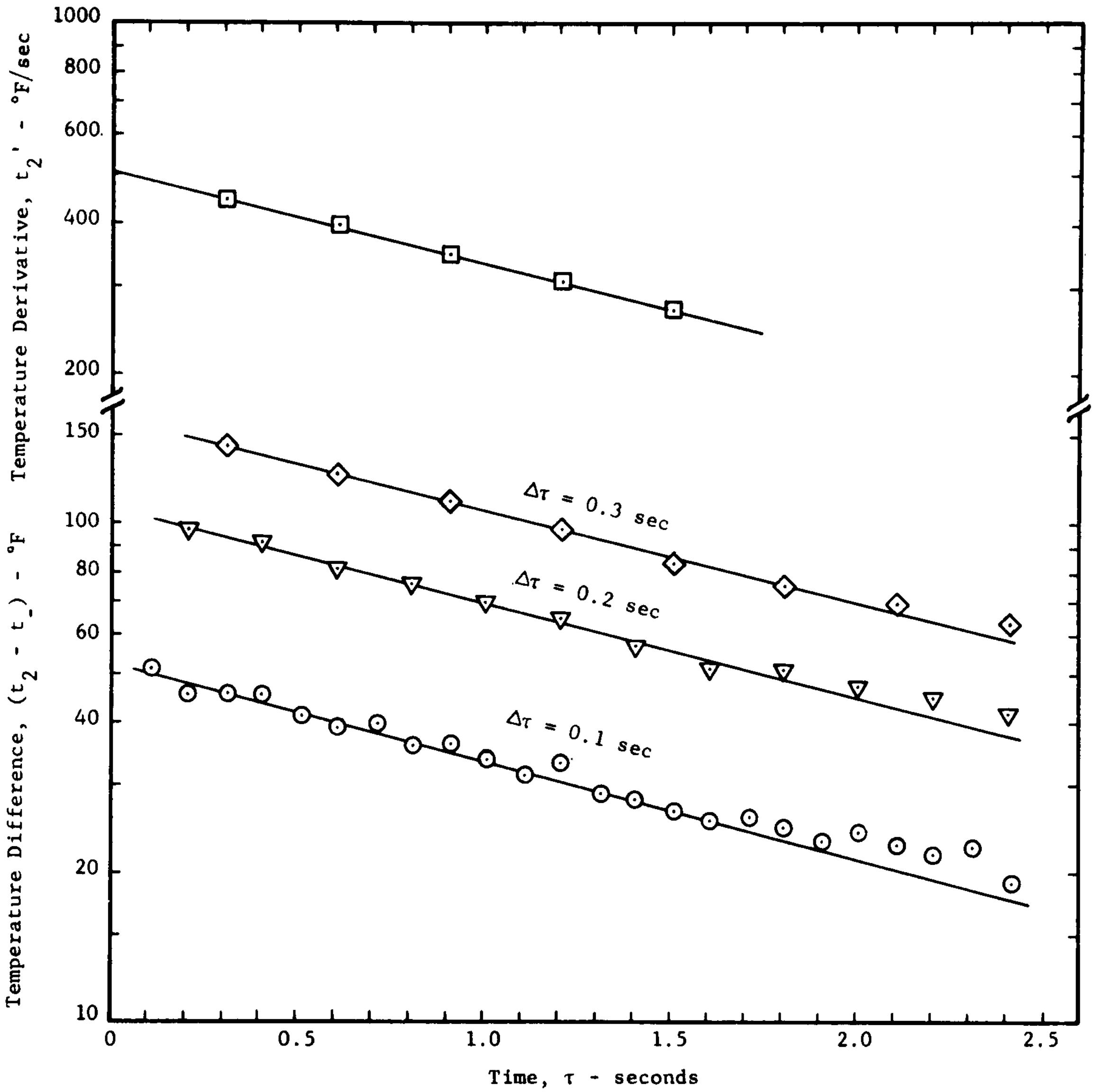
$$\Delta t_g / t_g = \pm \ 2.31\%$$

The average temperature evaluated from the dual-element transducer was 2258°F, representing a deviation of +10°F or +0.45% from the reference value of 2248.2°F; this deviation is less than the estimated error of the reference measurement itself.



CALCULATION OF TEMPERATURE DERIVATIVES, t_1',
FOR RUN C-8

FIGURE C-1



CALCULATION OF TEMPERATURE DERIVATIVES, t_2',
FOR RUN C-8

FIGURE C-2

UNCLASSIFIED

Aeronautical Research Laboratories, Wright-Patterson AFB, O. EXPERIMENTAL EVALUATION OF A DUAL-ELEMENT TRANSDUCER FOR HIGH TEMPERATURE-GAS MEASUREMENTS by J.T. Chambers, D. L. Rall, W.H. Giedt, Advanced Technolcgy Labs., Mountain View, Calif. March 1963. 47 p. incl. illus. tables. (Project 7063;Task 7063-01) (Contract AF 33(657)-8411) Unclassified Report

An experimental evaluation was made of a dual-element transducer, in which gas-stream temperatures are inferred from simultaneous temperaure-time measurements of two transducers of equal shape but unequal thermal

(over)

UNCLASSIFIED

UNCLASSIFIED

capacity. The major effort was expended on measuring medium temperature streams to prove the feasibility of the concept. The accuracy of the transducer was within ± 6% in measurements from 1950 to 2250°F, which was the best experimental accuracy predicted by an earlier analysis of the concept. A limited number of measurements were made with the transducer directly in an oxyacetylene flame. The indicated flame temperatures were 4700°F and 4789°F, which agree within 5% with measurements made by sodium-line-reversal techniques for equivalent combustion condictions in tests conducted at the University of California. In a third series of tests, the transducer was used to traverse a 2100°F gas stream, and from a single record the temperature profile in the stream was calculated within the accuracy to which the true profile could be established.

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, Wright-Patterson AFB, O. EXPERIMENTAL EVALUATION OF A DUAL-ELEMENT TRANSDUCER FOR HIGH TEMPERATURE-GAS MEASUREMENTS by J.T. Chambers, D. L. Rall, W.H. Giedt, Advanced Technolcgy Labs., Mountain View, Calif. March 1963. 47 p. incl. illus. tables. (Project 7063;Task 7063-01) (Contract AF 33(657)-8411) Unclassified Report

An experimental evaluation was made of a dual-element transducer, in which gas-stream temperatures are inferred from simultaneous temperaure-time measurements of two transducers of equal shape but unequal thermal

(over)

UNCLASSIFIED

UNCLASSIFIED

capacity. The major effort was expended on measuring medium temperature streams to prove the feasibility of the concept. The accuracy of the transducer was within ± 6% in measurements from 1950 to 2250°F, which was the best experimental accuracy predicted by an earlier analysis of the concept. A limited number of measurements were made with the transducer directly in an oxyacetylene flame. The indicated flame temperatures were 4700°F and 4789°F, which agree within 5% with measurements made by sodium-line-reversal techniques for equivalent combustion condictions in tests conducted at the University of California. In a third series of tests, the transducer was used to traverse a 2100°F gas stream, and from a single record the temperature profile in the stream was calculated within the accuracy to which the true profile could be established.

UNCLASSIFIED